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U.S. ARMY MISSILE RESEARCH AND DEVELOPMENT COMMAND

Redstone Arsenal, Alabama 35809

STORAGE RELIABILITY

OF

MISSILE MATERIEL PROGRAM

STORAGE RELIABILITY SUMMARY REPORT

VOLUME II

ELECTROMECHANICAL DEVICES

LC-78-2 FEBRUARY 1978

PRODUCT ASSURANCE DIRECTORATE

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This report contains the available information on storage failure rates for electromechanical devices, summarized from other reports on accelerometers, gyroscopes, relays, and switches. The information is part of a research program being conducted by the U. S. Army Missile R&D Command, Redstone Arsenal, Alabama. The objective of this program is the development of non-operating (storage) reliability prediction and assurance techniques for missile materiel. This report updates and replaces report LC-76-2 dated

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ABSTRACT

This report summarizes analyses on the non-operating reliability of missile materiel. Long term non-operating data has been analyzed together with accelerated storage life test data. Reliability prediction models have been developed for various classes of devices.

This report is a result of a program whose objective is the development of non-operating (storage) reliability prediction and assurance techniques for missile materiel. The analysis results will be used by U. S. Army personnel and contractors in evaluating current missile programs and in the design of future missile systems.

The storage reliability research program consists of a country wide data survey and collection effort, accelerated testing, special test programs and development of a non-operating reliability data bank at the U. S. Army Missile Research & Development Command, Redstone Arsenal, Alabama. The Army plans a continuing effort to maintain the data bank and analysis reports.

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1.0 INTRODUCTION

1.1 Missile Reliability Considerations

Materiel in the Army inventory must withstand long periods of storage and "launch ready" non-activated or dormant time as well as perform operationally in severe launch and flight environments. In addition to the stress of temperature soaks and aging, they must often endure the abuse of frequent transportation and handling and the climatic extremes of the forward area battlefield environment.

Missiles spend the majority of the time in this non-operating environment. In newer missile systems, complexity is increasing significantly, longer service lives are being required, and periodic maintenance and checkouts are being reduced. The combination of these factors places great importance on selecting missile materiels which are capable of performing reliably in each of the environments.

The inclusion of storage reliability requirements in the initial system specifications has also placed an importance on maintaining non-operating reliability prediction data for evaluating the design and mechanization of new systems.

1.2 Storage Reliability Research Program

An extensive effort is being conducted by the U. S. Army Missile Research & Development Command to provide detailed analyses of missile materiel and to generate reliability prediction data. A missile material reliability parts count prediction handbook, LC-78-1, has been developed and provides the current prediction data resulting from this effort.

This report is an update to report LC-76-2 dated May, 1976. It provides a summary of the analyses performed under the storage reliability research program and background information for the predictions in LC-78-1. Included are summaries of real time and test data, failure modes and mechanisms, and conclusions and recommendations resulting from analysis of the data. These recommendations include special design, packaging and product assurance data and information on specific part types and part construction.

For a number of the part types, detailed analysis reports are also available. These reports present details on part construction, failure modes and mechanisms, parameter drift and aging trends, applications, and other considerations for the selection of materiel and reliability prediction of missile systems.

The U. S. Army Missile Research & Development Command also maintains a Storage Reliability Data Bank. This data bank consists of a computerized data base with generic part storage reliability data and a storage reliability report library containing available research and test reports of non-operating reliability research efforts.

For the operational data contained in this report, the user should refer to the following sources: MIL-HDBK-217B, Military Standardization Handbook, Reliability Prediction of Electronic Equipment; Reliability Analysis Center (RAC) Microcircuit Failure Rates; RADC-TR-69-458, Revision to the Nonelectronic Reliability Handbook; and the Government-Industry Data Exchange Program (GIDEP) Summaries of Failure Rate Data.

1.3 Missile Environments

A missile system may be subjected to various modes of transportation and handling, temperature soaks, climatic extremes, and activated test time and "launch ready" time in addition to a controlled storage environment. Some studies have been performed on missile systems to measure these environments. A summary of several studies is presented in Report BR-7811, "The Environmental Conditions Experienced by Rockets and Missiles in Storage, Transit and Operations" prepared by the Raytheon Company, dated December 1973.

In this report, skin temperatures of missiles in containers were recorded in dump (or open) storage at a maximum of 165°F (74°C) and a minimum of -44°F (-42°C). In non-earth covered bunkers temperatures have been measured at a maximum of 116°F (47°C) to a minimum of -31°F (-35°C). In earth covered bunkers, temperatures have been measured at a maximum of 103°F (39°C) to a minimum of 23°F (-5°C).

Acceleration extremes during transportation have been measured for track, rail, aircraft and ship transportation. Up to 7 G's at 300 hertz have been measured on trucks; 1 G at 300 hertz by rail; 7 G's at 1100 hertz on aircraft; and 1 G at 70 hertz on shipboard.

Maximum shock stresses for truck transportation have been measured at 10 G's and by rail at 300 G's.

Although field data does not record these levels, where available, the type and approximate character of storage and transportation are identified and used to classify the devices.

1.4 System Level Analysis

The primary effort in the Storage Reliability Research Program is on analysis of the non-operating characteristics of parts. In the data collection effort, however, some data has been made available on system characteristics.

This data indicates that a reliability prediction for the system based on part level data will not accurately project maintenance actions if the missile is checked and maintained periodically. Factors contributing to this disparity include test equipment reliability, design problems, and general handling problems. In many cases, these problems are assigned to the system and not reflected in the part level analysis.

In general, a factor of 2 should be multiplied by the device failure rate to obtain the maintenance rate. Three system examples are described below:

1.4.1 System A

For system A, a check of 874 missiles in the field indicates 142 failed missiles. These failed missiles were taken to a maintenance facility. At the maintenance facility, no fault could be found in 51 of the missiles. Two missiles faults were corrected by adjustments. This left 89 failures which could be attributed to part failure. The parts were failure analyzed and the analysis indicated 19 failures to be a result of electrical overstress. These failures were designated design problems.

Therefore only 70 (49%) of the original 142 failures were designated as non-operating part failures.

1.4.2 System B

For system B, 26 missile failures were analyzed. Of these no fault was found in 2 missiles; adjustments were required for 2; external electrical overstress or handling damage was found in 10; a circuit design problem was assigned to 1, and component failures were assigned to 11.

1.4.3 Gyro Assemblies

An analysis of gyro assembly returns indicated that two thirds of the returns were attributed to design defects, mishandling, conditions outside design requirements, and to erroneous attribution of system problems.

Therefore, only 33 percent of the returns were designated as non-operating part failures.

1.5 Limitations of Reliability Prediction

Practical limitations are placed in any reliability analysis effort in gathering and analyzing data. Field data is generated at various levels of detail and reported in varying manners. Often data on environments, applications, part classes and part construction are not available. Even more often, failure analyses are non-existant. Data on low use devices and new technology devices is also difficult to obtain. Finally in the storage environment, the very low occurrence of failures in many devices requires extensive storage time to generate any meaningful statistics.

These difficulties lead to prediction of conservative or pessimistic failure rates. The user may review the existing data in the backup analyses reports in any case where design or program decision is necessary.

1.6 Life Cycle Reliability Prediction Modeling

Developing missile reliability predictions requires several tasks. The first tasks include defining the system, its mission, environments and life cycle operation or deployment scenario.

The system and mission definitions provide the basis for constructing reliability success models. The modeling can incorporate reliability block diagrams, truth tables and logic diagrams. Descriptions of these methods are not included here but can be studied in detail in MIL-HDBK-217B or other texts listed in the bibliography.

After the reliability success modeling is completed, reliability life cycle prediction modeling for each block or unit in the success model is performed based on the definitions of the system environment and deployment scenario. This reliability life cycle modeling is based on a "wooden round" concept in order to assess the missile's capability of performing in a no-maintenance environment. The general equation for this modeling is:

$$R_{LC} = R_{T/H} \times R_{STOR} \times R_{TEST} \times R_{LR/D} \times R_{LR/O} \times R_{L} \times R_{F}$$

where:

R_{LC} is the unit's life cycle reliability

$R_{T/H}$ is the unit's reliability during handling and transportation

R_{STOR} is the reliability during storage

R_{TEST} is the unit's reliability during check out and test

$R_{LR/D}$ is the unit's reliability during dormant launch ready time

$R_{LR/O}$ is the unit's reliability during operational (>10% electronic stress) launch ready time

R_{L} is the unit's reliability during powered launch and flight

R_{F} is the unit's reliability during unpowered flight

The extent of the data to date does not provide a capability of separately estimating the reliability of transportation and storage for missile materiel. Also data has indicated no difference between dormant (>0 and <10% electrical stress) and non-operating time. Therefore, the general equation can be simplified as follows:

$$R_{LC}(t) = R_{NO}(t_{NO}) \times R_{O}(t_{O}) \times R_{L}(t_{L}) \times R_{F}(T_{F})$$

where: R_{NO} is the unit's reliability during transportation and handling, storage and dormant time (non-operating time)

t_{NO} is the sum of all non-operating and dormant time

R_{O} is the unit's reliability during checkout, test or system exercise during which components have electrical power applied (operating).

t_O is the sum of all operating time excluding launch and flight

R_L is the unit's reliability during powered launch and flight (Propulsion System Active)

t_L is the powered launch and flight time

R_F is the unit's reliability during unpowered flight

t_F is the unpowered flight time

t is the sum of t_{NO}, t_O, t_L and t_F

The values R_{NO}, R_O, R_F are calculated using several methods. The primary method is to assume exponential distributions as follows:

$$R_{NO}(t_{NO}) = e^{-\lambda_{NO} t_{NO}}$$
$$R_O(t_O) = e^{-\lambda_O t_O}$$
$$R_L(t_L) = e^{-\lambda_L t_L}$$
$$R_F(t_F) = e^{-\lambda_F t_F}$$

The failure rates λ_{NO}, λ_O, λ_L and λ_F are calculated from the models in the following sections. λ_{NO} is calculated from the non-operating failure rate models. The remaining failure rates are calculated from the operational failure rate models using the appropriate environmental adjustment factors. Each prediction model is based on part stress factors which may include part quality, complexity, construction, derating, and other characteristics of the device.

Other methods for calculating the reliability include wearout or aging reliability models and cyclic or one shot reliability models. For each of these cases, the device section will specify the method for calculating the reliability.

1.7 Reliability Predictions During Early Design

Frequently during early design phases, reliability predictions are required with an insufficient system definition to utilize the stress level failure rate models. Therefore, a "parts count" prediction technique has been prepared. It provides average base failure rates for various part types and provides K factors for various phases of the system deployment scenario to generate a first estimate of system reliability. This prediction is presented in Report LC-78-1.

1.8 Summary of Report Contents

The report is divided into five volumes which break out major component or part classifications: Volume I, Electrical and Electronic Devices; Volume II, Electromechanical Devices; Volume III, Hydraulic and Pneumatic Devices; Volume IV, Ordnance Devices; and Volume V, Optical and Electro Optical Devices. Table 1-1 provides a listing of the major part types included in each volume.

1.9 Extent of Volume II Update

This report updates report LC-76-2, Volume II, dated May 1976. An additional 1.1 billion part hours and 109 failures have been analyzed. Table 1-2 summarizes the major changes that occurred in the analyses.

TABLE 1-1. REPORT CONTENTS

		Detailed Rept. Number & Date
Volume I	**Electrical and Electronic Devices**	
Section		
2.0	Microelectronic Devices	LC-78-IC1, 1/78
3.0	Discrete Semiconductor Devices	-
4.0	Electronic Vacuum Tubes	LC-78-VT1, 1/78
5.0	Resistors	-
6.0	Capacitors	-
7.0	Inductive Devices	-
8.0	Crystals	-
9.0	Miscellaneous Electrical Devices	-
10.0	Connectors and Connections	-
11.0	Printed Wiring Boards	-
Volume II	**Electromechanical Devices**	
Section		
2.0	Gyros	LC-78-EM1, 2/78
3.0	Accelerometers	LC-78-EM2, 2/78
4.0	Switches	LC-78-EM4, 2/78
5.0	Relays	LC-78-EM3, 2/78
6.0	Electromechanical Rotating Devices	-
7.0	Miscellaenous Electromechanical Devices	-
Volume III	**Hydraulic and Pneumatic Devices**	
Section		
2.0	Accumulators	LC-76-HP2, 5/76
3.0	Actuators	LC-76-HP3, 5/76
4.0	Batteries	LC-78-B1, 2/78
5.0	Bearings	-
6.0	Compressors	-
7.0	Cylinders	-
8.0	Filters	-
9.0	Fittings/Connections	-
10.0	Gaskets	-
11.0	O-Rings	-
12.0	Pistons	-
13.0	Pumps	LC-76-HP4, 5/76
14.0	Regulators	-
15.0	Reservoirs	-
16.0	Valves	LC-76-HP1, 5/76
Volume IV	**Ordnance Devices**	
Section		
2.0	Solid Propellant Motors	LC-76-OR1, 5/76
3.0	Igniters and Safe & Arm Devices	LC-76-OR2, 5/76
4.0	Solid Propellant Gas Generators	LC-76-OR3, 5/76
5.0	Misc. Ordnance Devices	-
Volume V	**Optical and Electro Optical Devices**	

TABLE 1-2. EXTENT OF VOLUME II UPDATE

SECTION	DEVICE	APPROX. NON-OPERATING DATA ADDED MILLION PART HRS.	FAILURES	MAJOR CHANGES IN NON-OPERATING FAILURE RATES
2.0	Gyroscopes	163.3	21	Decrease in Predicted Failure Rate
3.0	Accelerometers	95.2	3	Minor
4.0	Switches	235.8	21	Failure Rate Broken Out by Switch Types
5.0	Relays	90.5	3	Increase in Predicted Failure Rate
6.0	Rotating Devices	190.5	31	New Section
7.0	Miscellaneous Electromechanical Devices	374.0	25	New Section

2.0 Gyroscopes

A gyroscope is used to detect angular motion with respect to inertial (Newtonian) space. The usual construction is a spinning wheel, the angular momentum of which remains fixed in space if no external torques are applied. If such a wheel is forced to move about one axis, it will precess about another, and the precession motion, which can be conveniently measured, is proportional to the forced rotation. The usual construction uses single axis bearings for both the spinning wheel and the precession axes.

A primary distinction among gyros is between single degree of freedom and two degree of freedom gyros. Single degree of freedom gyros have only one gimbal axis, which means only one set of gimbal bearings, only one torquer and only one pickoff. Rate gyros and integrating rate gyros are single degree of freedom designs.

A two degree of freedom gyro (also called a free gyro) incorporates two gimbals, each with a pickoff and torquer, into the gyro itself. These gyros are often used in systems which provide a small alignment torque.

Because of its complexity, it is convenient to think of a gyro in terms of its functional components: wheel, spin bearings, spin motor, gimbal, pickoff and torquer.

The purpose of the wheel is to provide a large ratio of angular momentum to the disturbance torques in the system. Speeds of 12,000 or 24,000 rpm are typical. The wheel may be split into symmetrical halves, and the web of the wheel may be shaped to make the wheel isoelastic. Typical construction consists of a heavy rim supported by a conical web.

The spin bearings support the wheel both radially and axially, while allowing relatively free rotation. Ball bearings are typical, and provide a comparatively rigid support. They can be designed to be isoelastic and to provide axial support by using a large contact angle (about 35°).

Gas bearings have also been used for spin bearings. A typical design uses the spin itself to pull gas into the bearing so that no external supply is required.

The spin motor is typically a synchronous motor of the hysteresis type, either two or four pole. The supply is typically two phase 400 hertz. If the scale factor is critical a synchronous design must be used, but in systems where the gyro is simply driven to null an induction motor may be used. Power for the spin motor must be provided without introducing disturbance torques, typical practice is to use flexible leads in a configuration which can be compensated. Neither the hysteresis nor the induction design require electrical connection to the wheel assembly.

Where the gyro is only needed for a few minutes, a spring or squib may be used to bring the wheel up to speed before the start of the mission. No spin motor is then required.

The gimbal ring should be rigid, or at least isoelastic and must be carefully balanced. The gimbal bearings have little motion but must be as nearly torque free as possible. Some designs use ball bearings with dither or counter rotation of the fixed raceway to eliminate breakaway friction. Gas bearings are sometimes used, but an external gas supply is necessary.

Some designs use a fluid to float the weight supported on the gimbal bearings. The bearing load can be reduced by a factor of 1000 in this way, thus reducing those torques which are proportional to the bearing load.

The pickoff reads the angle thru which the gimbal bearing axis has been turned. It is important that the pickoff not introduce a reaction torque, so potentiometers are suitable only in low accuracy systems. Typical pickoffs use a differential transformer or an optical readout. A variable reluctance design can eliminate the moving coil and its connections in a differential transformer.

The torquer is almost invariably electromagnetic. The design can be very like that of the pickoff, except that currents flow in both sets of coils. The desired torque is determined in an electrical network outside the gyro.

Exotic gyroscopes using quite different principles should appear in production in the next few years.

2.1 Storage Reliability Analysis

2.1.1 Storage Failure Rates

The expected intrinsic storage failure rate for rate gyroscopes is 133 fits (failures per billion hours) with 90% confidence that the true failure rate lies below 175 fits. The following factors are suggested as being consistent with the data available:

- ° For free gyros, multiply by a factor of 2.
- ° For replacement rate, multiply by a factor of 3.

This study is based upon the 835 million part-hours collected to date containing 209 failures. The data includes eight missile programs, three space applications and one report for which the application was not identified. Nearly all of the data is for rate gyros. For gyroscopes showing failures, a range of failure rates from 121 to 524 fits was observed.

A comparison with operating data indicates that the operating failure rate in a ground environment is about 196 times the storage failure rate, and the operating failure rate in the missile launch environment is about 4000 times the storage failure rate.

2.1.2 Data Description

Data was collected from twelve sources, eight of which are missile programs. The data summarized in Table 2.1-1 represents 835 million gyro non-operating hours with 209 failures reported. The failure rates for each source are calculated in fits (failures per billion hours) and are the maximum likelihood values. One failure is assumed in the failure rate calculation if there were no failures reported. Failures attributable to design defects which have been corrected, to mishandling, to conditions outside design requirements, and to erroneous attribution of system problems have not been included.

Where identified, the data includes gyros with ages up to 6.3 years. For several sources, it was necessary to estimate the part non-operating hours as indicated in Table 2.1-1. These estimates are conservative and part non-operating hours could have been greater than indicated. Each data source is described in more detail below.

Some differences could be anticipated between the data sources due to differences in the design and in the testing (screening) in the various programs. For the programs with large exposure, the components listed represent production over extended periods of time, which means that both the design and the production process have varied. Since those failures which were remedied are not counted, the failure rates should represent those attained at the end of the project, i.e., by the "mature" design.

For examples, a step was added to gyro manufacture in Source M-2 to saturate the exposed plastic with the damping fluid by exposing it under high pressure. This prevents subsequent change in the volume of the damping fluid. In the gyros for Missile M, a set of sliding contacts was replaced by a flex lead, and later the material of the flex leads was changed to avoid a corrosion problem.

Each data source is described in more detail below.

2.1.2.1 Source A Data

Source A represents a reliability study performed under contract to RADC. This source identified the type and quality grades for the devices, however, it provided no information regarding storage conditions or individual programs.

2.1.2.2 Source B Data

The storage data under Source B actually represents standby data in an orbiting satellite environment. No failures were indicated in 76 thousand gyro standby hours.

2.1.2.3 Source L Data

Source L represents a special test program for gyros designed for a surface-to-surface missile. Six gyros were stored in a controlled environment for 6.3 years with no failures reported.

TABLE 2.1-1 GYRO NON-OPERATING DATA

SOURCE	NO. OF DEVICES	MILLION PART STORAGE HRS.	FAILURES	FAILURE RATE IN FITS
A	-	34.367	18	524.
B	15	.076	0	(<13158.)
L	6	.331	0	(<3021.)
M-1	115	4.44*	0	(<225.)
M-2	102	3.94*	1	254.
MISSILE				
E-1	4370	63.802	23	360.
F	120	2.628	0	(<380.)
G	39	1.118	0	(<894.)
H	5355	85.1	13	153.
I	8280	82.36	10	121.
M	-	30.6*	16	523.
T	12000	525.6	128	244.
U	15	.657	0	(<1522.)
	TOTALS	835.019	209	250.3

*Estimated part hours

2.1.2.4 Source M Data

The first entry in Table 2.1-1 under source M represents spacecraft platform gyros which are man-rated. These are the most expensive gyros in Table 2.1-1.The platforms stored in a controlled environment were retested once per year. None of the gyros have been outside of the operational specifications. Average age is 5.3 years.

The second entry under source M also represents spacecraft gyros. These gyros, stored under the same conditions, are man-rated, however they are used in a redundant configuration. One failure was reported as a result of a spin bearing seizure. Other failures attributed to damping fluid volume loss were not included since they were considered design defects.

2.1.2.5 Missile E-1 Data

Missile E-1 data consists of 874 missiles stored for 20 months. The missiles were stored in containers exposed to external environmental conditions in the northeast U. S. They were also transported once from coast to coast. Each missile contains five rate gyros. A total of twenty three gyro failures were reported.

2.1.2.6 Missile F Data

Missile F data consists of 120 missiles, 60 of which were stored for one year and 60 for two years. The missiles in storage containers experienced the following environments: 30 missiles stored outside in the Arctic on wooden racks with canvas covers; 30 missiles stored outside in the southeast desert under open sided metal roof sheds; 30 missiles stored outside in the canal zone under open sided metal roof sheds; and 30 missiles stored in the southeast U. S. in bunkers. No gyro failures have been reported.

2.1.2.7 Missile G Data

Missile G data consists of 39 missiles stored for periods from 28 months to 56 months for an average storage period of 39 months. The missiles in storage containers experienced the following environments: 12 missiles stored outside in the southeast desert; 12 missiles stored outside in the northeast U. S.; 12 missiles stored on the Gulf Coast; and 23 missiles stored in bunkers in the southeast U. S. No gyro failures have been reported.

2.1.2.8 Missile H Data

Missile H data represents field data from a recent army missile program fielded in the 1970's. The major item in which the devices were assembled was subjected to operating times at high and low temperatures, shock and vibration. The missiles were transported overseas and stored for various lengths of time. No tests were run until the missiles were removed from storage and returned to the states. Storage durations varied from 6 months to 6 years with an average time of 1.8 years. Storage environments included cannister time in a controlled environment, cannister time subject to outside elements and missile time on pallets and on launchers. A number of samples were also run through road tests under field conditions. Each missile containing five rate gyros. Thirteen gyro failures have been reported.

2.1.2.9 Missile I Data

Missile I data consists of 2,070 missiles stored for periods from 1 month to 40 months for an average storage period of 14 months. Approximately 80 percent of the missiles were stored in U. S. depots while the remainder were stored at various bases around the country. Ten gyro failures have been reported.

2.1.2.10 Missile M Data

Missile M data represents a surface-to-surface missile. Data was available on approximately 13 years of depot repair history. The data includes some operating time, typically 290 hours. Failure anlaysis was performed on these gyros indicating the main failure mode to be "open torquer windings."

2.1.2.11 Missile T Data

Missile T data represents a surface-to-air missile. Data on a 3000 missile inventory for an average of 5 years is included. At test, missile ages ranged from 6 months to 8 years. The missiles, built in the 1954 time frame, contained a gyro package with three rate gyros and one free gyro. The data indicated 128 gyro package failures. Periodic testing performed on the gyro packages was limited. It consisted of swinging the missile and observing gyro outputs for proper polarity. Only catastrophic failures could be seen, and these are identified only to the package level.

2.1.2.12 Missile U Data

Missile U data represents an air-to-surface missile. Data on 15 missiles stored for five years is included. Five missiles were stored for a year in a tropic zone and five in an arctic zone. No failures in the gyros themselves were reported, however, three failures in solder joints to gyro initiators were attributed to corrosion from heat, humidity and salt (tropic zone). Solder is chemically attacked under these conditions, and these failures are classified as a design defect.

2.1.3 Data Evaluation

Pooling all of the sources results in 209 failures in 835.019 million storage hours giving a failure rate of 250 fits. A decision was made to remove the data set for Missile T because failures were identified only at the platform level and may have been a result of other components. The remaining sources show 81 failures in 309.418 million storage hours giving a failure rate of 262 fits (virtually the same as with Missile T included).

The failure rates for those sources showing failures ranged from 121 to 524 fits. A test of significance (described in Appendix A) was performed to test whether a single failure could describe all the data sets. The test indicated that there was a significant difference with three data sets having signficantly higher failure rates. These three data sets were placed into a separate group. Then the two groups were tested and no significant differences were indicated. The pooled data for the two groups are shown in Table 2.1-2.

The group 1 data in Table 2.1-2 includes source A data for which little detail is available, however, at least a major portion is from the 1960's time frame. Missile E-1 is early 1960's program with the tests performed in 1968. Missile M is also late 50's and early 1960 technology. Therefore the data in group 1 primarily represents 1960 technology.

The group 2 data represents a wide range of applications. Sources B, M-1 and M-2 represent spacecraft programs while missile programs F and G represent mid to late 1960's technology and missiles H and I early 1970 technology. The lower failure rate for this group would tend to indicate an improvement in gyro design for storage reliability. Therefore, a non-operating failure rate for current technology gyros is estimated to be 133 fits and a 90% confidence that the time failure rate lies below 175 fits.

Nearly all of the data analyzed is for rate gyros. Free gyros with two, rather than one, sets of gimbal bearings should not exceed twice the failure rate as that calculated for rate gyros.

Field data has indicated that component replacement rates exceed component failure rates. This results from replacements for components accidentally damaged (overheating is a common cause) or replacements for components removed without test in the course of trying to repair a system. The data from Missile M indicated the replacement rate approached three times the failure rate.

2.2 Operational/Non-Operational Reliability Comparison

Operational failure rate data for rate gyroscopes was

TABLE 2.1-2. POOLED DATA GROUPS

GROUP 1

SOURCE	NO. OF DEVICES	MILLION PART STORAGE HRS.	FAILURES	FAILURE RATE IN FITS
A	-	34.367	18	524.
Missile E-1	4370	63.802	23	360.
Missile M	-	30.6	16	523.
TOTALS		128.769	57	443.

GROUP 2

SOURCE	NO. OF DEVICES	MILLION PART STORAGE HRS.	FAILURES	FAILURE RATE IN FITS
B	15	.076	0	(<13158.)
L	6	.331	0	(<3021.)
M-1	-	4.44	0	(<225.)
M-2	-	3.94	1	254.
MISSILE				
F	120	2.628	0	(<380.)
G	39	1.118	0	(<894.)
H	5355	85.1	13	153.
I	8280	82.36	10	121.
U	15	.657	0	(<1522.)
TOTALS		180.65	24	133.

extracted from report RADC-TR-74-268, Revision of RADC Non-electronic Reliability Notebook, D. F. Cottrell, et al, Martin Marietta Aerospace, dated October 1974. This data is shown in Table 2.2-1 and compared with the non-operating failure rate prediction. Comparing the common environment (ground) indicates a non-operating to operating ratio of 1 : 196.

TABLE 2.2-1. OPERATIONAL/NON-OPERATIONAL RELIABILITY COMPARISON

ENVIRONMENT	PART HRS. (10^6)	NO. OF FAILURES	FAILURE RATE IN FITS	$\lambda_{op}/\lambda_{no}$
Non-operating				
Ground, Fixed	180.65	24	133	-
Operating				
Ground	1.269	33	26005	196.
Ground, Mobile	.012	3	333333	2506.
Airborne	14.56	5413	371798	2795.
Missile	.048	26	541667	4073.
Helicopter	.255	65	254902	1917.

2.3 Conclusions & Recommendations

Data collected has primarily been for rate gyros. The demonstrated intrinsic storage failure rate for rate gyros is near 133 fits. Data indicates that the non-operating reliability of gyroscopes has improved in the last ten years. Substantially higher reliability for gyros is within the state of the art but only at a significantly higher expense. Novel techniques in development look promising from a reliability standpoint.

Areas identified which are important factors in gyro storage reliability are discussed below.

2.3.1 Spin bearing lubrication - One program has adopted a procedure of operating the gyro every 6 months while in storage, and has incorporated a spin detector so that rotation of the wheel can be verified easily. Some lubricants are more liable to separate than others, and selection of lubricant is important. Drying or oxidation are other concerns. The lubrication problem can be avoided entirely by using hydrodynamic spin bearings, which use the fill gas as a lubricant.

2.3.2 Creep due to temperature change - This effect appears because it is not possible to build the gyro from a single material - insulators, conductors, and magnetic materials are used. Storage at constant temperature is a possible solution.

2.3.3 Creep and dimensional change due to phase change - This effect can be thought of as a low temperature annealing process. Possibly material selection could be used to minimize the effect.

Both of the creep effects can be accommodated by rebalancing the gyro as needed.

2.3.4 Magnetic fields - Since the gyro contains magnetic material, the magnetic environment needs to be controlled also. Large fields will change the permanent magnetism, resulting in uncompensated torques. Mu-metal shields may be used in high precision designs.

2.3.5 Adhesion - A program using gas bearings reports adhesion due to high contact pressure when the gyro is stored undisturbed. The bearing material was a ferrous base, not ceramic. A possibility is to store gas wheel bearings with the wheel spinning (power on). Another is to turn the gyro over periodically.

Gimbal gas bearings could be mechanically supported in storage, which would also be desirable for shipping (shock and vibration).

2.3.6 Burn-in - An MIT paper (Ref. 7, p. 475) comments that "A test program ... (should be) made equal to 10 or 15 per-cent of Required Reliability Performance Life." No supporting data is given, but an artificial example is shown.

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Note: Inertial guidance is a fast-moving field. The current literature should be surveyed for recent developments. (This survey made January 1975.) Much of the literature is classified.

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3.0 Accelerometers

An accelerometer is designed using the Newtonian relation $F = ma$. A known proof mass, m, is constrained to follow the motion of the case of the device by means of a constraining force, F, which is measured, whence the acceleration, a, can be calculated. As a matter of convenience, the measurement is often made only along a single axis. The constraining force can be provided in a number of ways, some of which are:

a) by a simple spring. The relative displacement is the measure of the force. This configuration is not much used, because only a low accuracy is possible.

b) by an unsaturated electromagnet. The current is proportional to the force. In some designs, the current is a pulse of fixed magnitude and duration, a count of the number of pulses is then proportional to the velocity acquired.

c) by a gyroscope. The precession rate is proportional to the acceleration. This configuration is usually used with a servo to null the precession angle.

d) by a set of taut wires. The tension in each wire is determined by using a pickoff and exciter to determine its resonant frequency.

In inertial applications, the integral of the acceleration (velocity gained) is usually wanted. If this is done within the accelerometer, it is termed an integrating accelerometer or a velocity meter.

3.1 Storage Reliability Analysis

3.1.1 Storage Failure Rates

The best observed failure rate for accelerometers is 29.7 fits (failures per billion hours), with 90% confidence that the true failure rate lies below 59 fits. Observed failure rates range up to 1923 fits.

3.1.2 Data Description

Data was received from 5 sources and 6 missile programs representing 448.5 million non-operating hours with 196 failures reported. Analysis of the data indicated that the data from two missile programs could not be used in deriving a non-operating failure rate.

All of the data is shown in Table 3.1-1. Missile M data listed accelerometer removals, however, no analysis was performed to determine the actual number of failed units. Missile T data recorded assembly failures. The assemblies consisted of two accelerometers, a roll free gyro and a roll corrector. Data was unavailable to determine which assembly failures were a result of accelerometer failures.

The remaining data includes 137.8 million non-operating hours with 10 failures giving an average non-operating failure rate of 73 fits (failures per billion hours). The failure rates for sources indicating failures range from 24 fits to 1923 fits.

Each data source is discussed below.

3.1.2.1 Source A Data

Source A represents a reliability study performed under contract to RADC in 1974. This source identified the type and quality grades for the devices, however, it provided no information regarding storage conditions or individual programs.

3.1.2.2 Source B Data

The storage data under Source B actually represents standby data in an orbiting satellite environment. No failures were indicated in 110 thousand accelerometer standby hours.

3.1.2.3 Source C Data

Source C represents a reliability study performed under contract to RADC in 1968. It included 2506 devices stored for an average of 5 months. The devices were missile hardware. No failures were reported.

TABLE 3.1-1. ACCELEROMETER NON-OPERATING DATA

SOURCE	NO. OF DEVICES	MILLION PART STORAGE HRS.	FAILURES	FAILURE RATE IN FITS	COMMENT
A	-	3.12	6	1923.	Pendulum
A	-	0.25	0	<4000.	Angular
A	-	0.46	0	<2174.	Linear
B	18	0.11	0	<9091.	
C	2506	9.3	0	<108.	
M	115	4.44	0	<225.	2df Pendulum
P	34	1.30	1	769.	
MISSILE					
E-1	1748	25.521	0	<39.	
G	39	1.118	1	894.	
H	1071	17.015	1	59.	Linear
H	2142	34.029	0	<29.	Angular
I	4140	41.18	1	24.	
SUB TOTAL		137.843	10	73.	
OTHER DATA					
MISSILE M	-	30.6	76	2484.	76 removals
MISSILE T	6000	310.	105	349.	Assy. Failures
TOTAL		448.533	196	437.	

3.1.2.4 Source M Data

Source M represents spacecraft accelerometers which were part of systems stored in a controlled environment. The systems were tested once per year with no accelerometer failures reported. Average age of accelerometers at last test were 5.3 years.

3.1.2.5 Source P Data

Source P data represents a special aging and surveillance program. Devices are stored in a controlled environment. One device failed in a storage test at age three months. No failure analysis was available, however, the device was listed as not repairable. Two other devices failed tests, however, on retest, both devices performed satisfactorily. At last test, devices ranged in age from 1 month to 74 months. Average age was 52 months. No aging trends are evident from the tests.

3.1.2.6 Missile E-1 Data

Missile E-1 data consists of 874 missiles stored for 20 months. The missiles were stored in containers exposed to external environmental conditions in the northeast U. S. They were also transported once from coast to coast. No accelerometer failures were reported when tested at 20 months.

3.1.2.7 Missile G Data

Missile G data consists of 39 missiles stored for periods from 28 months to 56 months for an average storage period of 39 months. The missiles in storage containers experienced the following environments: 12 missiles stored outside in the southeast desert; 12 missiles stored outside in the northeast U. S.; 12 missiles stored on the Gulf Coast; and 23 missiles stored in bunkers in the southeast U. S. One accelerometer failure has been reported at age 47 months. Failure analysis indicated a failed thermistor (possibly due to electrical overload).

3.1.2.8 Missile H Data

Missile H data represents field data from a recent army missile program fielded in the 1970's. The major item in which the devices were assembled was subjected to operating times at high and low temperatures, shock and vibration. The missiles were transported overseas and stored for various lengths of time. No tests were run until the missiles were removed from storage and returned to the states. Storage durations varied from 6 months to 6 years with an average time of 1.8 years.

Storage environments included cannister time in a controlled environment, cannister time subject to outside elements and missile time on pallets and on launchers. A number of samples were also run through road tests under field conditions. One linear accelerometer failure was recorded at age 26 months. Failure analysis indicated a poor bond on accelerometers silicon beam (sensing element).

3.1.2.9 Missile I Data

Missile I data consists of 2,070 missiles stored for periods from 1 month to 40 months for an average storage period of 14 months. Approximately 80 percent of the missiles were stored in U. S. depots while the remainder were stored at various bases around the country. One accelerometer failure was recorded at age 14 months. No failure analysis was available.

3.1.2.10 Missile M Data

Missile M data represents a surface-to-surface missile: Data was available on approximately 13 years of depot repair history. With 30.6 million hours exposure, there were 76 accelerometer removals,however it was not possible to determine the number that were actually failed units. Based on gyro records for the same system, the failed units would account for only .5 to .33 of the removals.

3.1.2.11 Missile T Data

Missile T data represents a surface-to-air missile. Data on a 3,000 missile inventory for an average of 71 months is included. At test, missile ages ranged from 6 months to 8 years. The missiles, built in the 1954 time frame, contained an assembly with two accelerometers, a roll free gyro, and a roll connector. Data was unavailable to determine which assembly failures were a result of accelerometer failures.

3.1.3 Data Evaluation

Pooling data from the useable sources results in 10 failures in 137.843 million storage hours giving a failure rate of 73 fits. The failure rates for those sources showing failures range from 24 to 1923 fits. A test of significance (described in Appendix A) was performed to test whether a single failure rate could describe all the data sets. The test indicated that there was a significant difference with one data set having a significantly higher failure rate. This data set was removed and the remaining data sets retested indicating no significant differences.

The pooled data is shown in Table 3.1-2 with 134.723 million storage hours and 4 failures. The non-operating failure rate based on this data is 29.7 fits with a 90% confidence that the failure rate is less than 59 fits. The average age of the pooled data sets is 16 months with the oldest units being 74 months old.

No factors can be identified to account for the larger reported failure rate for pendulum accelerometers in Source A. The sources showing the lowest failure rates (Missiles H and I) are also the newest systems in the data sets. Both systems are early 1970 technology.

TABLE 3.1-2. POOLED DATA SETS

SOURCE	NO. OF DEVICES	MILLION PART STORAGE HRS.	FAILURES	FAILURE RATE IN FITS
A	-	0.25	0	<4000.
A	-	0.46	0	<2174.
B	18	0.11	0	<9091.
C	2506	9.3	0	<108.
M	115	4.44	0	<225.
P	34	1.30	1	769.
MISSILE				
E-1	1748	25.521	0	<39.
G	39	1.118	1	894.
H	1071	17.015	1	59.
H	2142	34.029	0	<29.
I	4140	41.18	1	24.
TOTALS		134.723	4	29.7

3.2 Operational/Non-Operational Reliability Comparison

Operational failure rate data for accelerometers was extracted from report RADC-TR-74-268, Revision of RADC Nonelectronic Reliability Notebook, D. F. Cottrell, et al, Martin Marietta Aerospace, dated October, 1974. This data is shown in Table 3.2-1 and compared with the non-operating failure rate prediction. Comparing the common environment (ground) indicates a non-operating to operating ratio of 1:1768.

TABLE 3.2-1. OPERATIONAL/NON-OPERATIONAL RELIABILITY COMPARISON

ENVIRONMENT	PART HOURS (10^6)	NO. OF FAILURES	FAILURE RATE IN FITS	$\lambda_{op}/\lambda_{no}$
Non-Operating				
Ground, Fixed	134.723	4	29.7	-
Operating				
Satellite	.112	0	<8179.	275.
Ground	9.234	485	52523.	1768.
Ground, Mobile	.037	0	<24757.	834.
Airborne	11.07	2619	236607.	7967.

3.3 Failure Modes & Mechanisms

Reference 8 (p. 56) contains a rough classification of accelerometer failures. Most of the failures reported there reflect a contamination problem. The two failure causes reported in the non-operating data appear to be random type occurrences. No aging trends have been indicated in any of the data.

3.4 Conclusions and Recommendations

Accelerometers do not appear to present any significant reliability problems in storage. The random failures that have been reported appear to be a result of slight weaknesses in the parts in manufacture or in the testing process. No aging trends have been identified for devices up to 74 months in age.

The non-operating failure rate developed in this report of 27.9 fits is recommended as being representative of the current technology.

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4.0 Switches

This section presents reliability analysis and data on electromechanical switches. Switches are sometimes classified by the actuating force (inertial, pressure, push, etc.) or by the mechanical features (toggle, stepping, rotary, etc.)

4.1 Storage Reliability Analysis

4.1.1 Storage Failure Rates

Storage data for switches was collected showing 65 failures in 698.6 million part hours. Predicted non-operating failure rates for various switch types are given in Table 4.1-1. Also included is the 90% confidence limit. The true failure rate should lie below this limit with 90% confidence.

TABLE 4.1-1. SWITCHES NON-OPERATING FAILURE RATES

TYPE	FAILURE RATE IN FITS*	90% CONFIDENCE LIMIT
General	82.8	125.3
Toggle/Pushbutton	26.0	101.1
Pressure	54.2	108.4
Thermal	17.1	66.6
Sensitive	82.6	125.3
Stepping	400.	1064.
Manual Rotary S&A	82.6	125.3
Solenoid	109.3	172.7
Motor Driven S&A	138.2	218.5
Inertial	66.4	98.7

*Failures per billion hours

4.1.2 Data Description

Switch non-operating data was obtained from four sources and four missile programs. The data represents 698.6 million switch non-operating hours with 65 failures reported. The data broken out by switch type is presented in Table 4.1-2. For those entries showing failures, the failure rate ranges from 29.4 fits (failures per billion hours) to 1130 fits.

Each data source is described in detail below.

4.1.2.1 Source A Data

Source A represents a reliability study performed under contract to RADC in 1974. This source identified the type and quality grades for the devices, however, it provided no information regarding storage conditions or individual programs. Data was available on toggle/pushbutton, pressure, sensitive, stepping, and inertial switches as well as a "general" category of switches. Failures were reported for pressure switches (4 failures in 48.3 million hours); stepping switches (2 failures in 5 million hours), and inertial switches (9 failures in 137.1 million hours). No data was given on failure mode or mechanisms.

4.1.2.2 Source C Data

Source C represents a reliability study performed under contract to RADC in 1968. No environments were provided. Data was available on toggle/pushbutton, pressure, thermostatic, sensitive and inertial switches as well as a "general" category of switches. Failures were reported for "general" switches (11 failures in 89.5 million hours), pressure switches (10 failures in 31 million hours), and inertial switches (6 failures in 25.3 million hours). No failure modes or mechanisms were provided.

4.1.2.3 Source P Data

Source P represents a special aging and surviellance program. Devices are stored in a controlled environment. Data was available on three types of inertial switches.

The first data entry in Table 4.1-2 represents a 3-G switch. Forty switches were tested having an average age of 64 months (the oldest switch was 66 months). No failures were recorded on this switch.

The second data entry for source P in Table 4.1-2 represents a safety inertial switch. Forty switches were also tested having an average age of 61 months (the oldest switch was 67 months). Two failures were recorded with the following causes given: 1) Corrosion on shaft - age 60 months; 2) Escapement mechanism slippage - age 56 months. Six other failures were recorded but they were not classified as catastrophic. Four of these were classified as failure cause unknown (ages: 35, 37, 56 and 64 months) and the switches tested satisfactorily in later tests. The fifth failure was classified as "improper clearance between pinion gear and timing weight (age 60 months) and the sixth failure as "foreign particle between pinion gear and timing weight" (age 51 months). Both switches tested satisfactorily at a later test.

The third data entry for source P in Table 4.1-2 represents a magnetic inertial switch. Twenty three switches were tested having an average age of 32 months (the oldest switch was 33 months). No failures were recorded on this switch.

4.1.2.4 Source R Data

Source R data represents a safe and arm (S&A) switch as analyzed in report LC-76-OR2. The inertial S&A data represents two missile programs. For these switches acceleration of the missile causes a g-weight to move which causes a rotary switch and a blocking rotor to rotate. Rotation of the blocking rotor arms the igniter mechanically by opening the ignition ports between the electrical squibs and the ignition pellets. The igniter is electrically armed by the rotation of the rotary switch, closing the igniter electric circuit.

The first inertial S&A program tested 21 switches with ages ranging from 45 to 91 months for an average age of 65 months. No failures were recorded on these switches.

TABLE 4.1-2. SWITCH NON-OPERATING DATA

SWITCH TYPE	SOURCE	NO. OF DEVICES	NON-OP. HRS. IN MILLIONS	NO. OF FAILURES	FAILURE RATE IN FITS
General	A	-	43.328	0	(<23.1)
	C	-	6.658	0	(<150.2)
	C	-	.1665	0	(<6006.)
	C	-	3.095	0	(<323.1)
	C	-	.2418	0	(<4136.)
	C	-	38.688	4	103.4
	C	-	37.2	6	161.3
	C	-	3.442	1	290.5
(TOTAL GENERAL			132.819	11	82.8)
Toggle/ Pushbutton	A	-	.603	0	(<1658.)
	A	-	1.01	0	(<990.)
	C	-	.0555	0	(<18018.)
	C	-	.3699	0	(<2703.)
	C	-	.1775	0	(<5634.)
	C	-	1.274	0	(<785.)
	Missile E-1	874	12.76	0	(<78.4)
	Missile F	240	5.256	0	(<190.)
	Missile H	1071	17.0	1	58.8
(TOTAL TOGGLE/PUSHBUTTON			38.5059	1	26.0)
Pressure	A	-	48.3	4	82.8
	C	-	31.001	10	322.6
	Missile E-1	1748	25.52	0	(<39.2)
(TOTAL PRESSURE			104.821	14	133.6)
Thermostatic	C	-	3.699	0	(<270.3)
	C	-	.0663	0	(<15083.)
	C	-	.111	0	(<9001.)
	Missile H	2142	34.0	1	29.4
	Missile I	2070	20.59	0	(<48.6)
(TOTAL THERMOSTATIC			58.4663	1	17.1)
Sensitive	A	-	1.644	0	(<608.3)
	C	-	.3699	0	(<2703.)
(TOTAL SENSITIVE			2.0139	0	(<496.5)
Stepping	A	-	5.00	2	400.
Manual Rotary S&A	R	101	3.574	0	(<280.)

TABLE 4.1-2. SWITCH NON-OPERATING DATA (cont'd)

SWITCH TYPE	SOURCE	NO. OF DEVICES	NON-OP. HRS. IN MILLIONS	NO. OF FAILURES	FAILURE RATE IN FITS
Solenoid	Missile I	8280	82.36	9	109.3
Motor Driven (S&A)	R	2016	65.104	9	138.2
Inertial	A	-	137.1	9	65.6
	C	-	25.337	6	236.8
	P	40	1.87	0	(<535.)
	P	40	1.77	2	1130.
	P	23	.54	0	(<1852.)
	R	21	.992	0	(<1008.)
	R	74	5.007	1	199.7
	Missile E-1	874	12.76	0	(<78.4)
	Missile I	2070	20.59	0	(<48.6)
(TOTAL INERTIAL			205.966	18	87.4)

The second inertial switch program tested 74 switches with ages ranging from 40 to 138 months for an average age of 93 months. One catastrophic failure was recorded where an improperly manufactured cover plate caused the arming socket to be improperly placed and interference between the rotary switch and the electrical contacts prevented the switch shaft from rotating. These switches were supposedly tested when placed into the inventory. Ten other failures were recorded as specification failures. Six failed to arm within the maximum specified time and four armed sooner than the minimum specified time. These specification failures were marginal and would not have affected the mission. Causes for two failures were identified: 1) misaligned gear train caused by two screws on the g-weight shafts being loose; and 2) improperly manufactured cover plate.

The manual rotary S&A data represents one missile program. The program tested 101 switches ranging in age from 9 to 75 months with an average age of 48 months. No failures were recorded.

The motor driven S&A data represents one missile program. The program tested 2017 switches ranging in age from 12 months to 96 months with an average age of 44 months. Nine failures were recorded as fails to arm or disarm. Thirty five failures were reported in which arming times exceeded minimum mission requirements. Note that this program had very stringent requirements on arming time. Forty nine failures were reported in which arming or safing times exceeded original acceptance specifications, however did meet mission requirements.

No detailed failure mechanism analysis was performed, however, age sensitive items were noted. These included swelling, cracking and general materiel degradation of O-rings, packing and insulators. Corrosion of bearings, contacts, switch ports, gear assemblies and motor armature were also postulated. Load relaxation of helical compression springs and bonding of friction plate clutch assembly were also noted.

Eighty percent of the failures involved long arming times. An age trend analysis was performed on the parametric data. The analysis indicated an average increase in arming time of 13 percent per year.

4.1.2.5 Missile E-1 Data

Missile E-1 data consists of 874 missiles stored for 20 months. The missiles were stored in containers exposed to external environmental conditions in the northeast U. S. They were also transported once from coast to coast. Data was available on toggle, pressure and inertial switches. No failures were recorded.

4.1.2.6 Missile F Data

Missile F data consists of 120 missiles, 60 of which were stored for one year and 60 for two years. The missiles in storage containers experienced the following environments: 30 missiles stored outside in the Arctic on wooden racks with canvas covers; 30 missiles stored outside in the southeast desert under open sided metal roof sheds; 30 missiles stored outside in the canal zone under open sided metal roof sheds; and 30 missiles stored in the southeast U. S. in bunkers. Data was available on toggle switches. No failures were reported.

4.1.2.7 Missile H Data

Missile H data represents field data from a recent army missile program fielded in the 1970's. The major item in which the devices were assembled was subjected to operating times at high and low temperatures, shock and vibration. The missiles were transported overseas and stored for various lengths of time. No tests were run until the missiles were removed from storage and returned to the states. Storage durations varied from 6 months to 6 years with an average time of 1.8 years. Storage environments included cannister time in a controlled environment, cannister time subject to outside elements and missile time on pallets and on launchers. A number of samples were also run through road tests under field conditions. Data was available on pushbutton and thermostatic switches. The one failure of a pushbutton switch was recorded as a bent leaf spring contact. No failure analysis was available on the thermal switch.

4.1.2.8 Missile I Data

Missile I data consists of 2,070 missiles stored for periods from 1 months to 40 months for an average storage period of 14 months. Approximately 80 percent of the missiles were stored in U. S. depots while the remainder were stored at various bases around the country. Data was available on thermostatic, inertial and solenoid switches. No failures were reported for the thermostatic or inertial switches. Nine failures were recorded on the solenoid switches. No failure analysis was available on these switches, however the main failure mode was "intermittent."

4.1.3 Data Evaluation

The data from the various sources were combined by device type as shown in Table 4.1-2. A test of significance (see Appendix A) was performed to test whether there was any significant differences in the data entries under each device type. Two device types, pressure switches and inertial switches, indicated a significant difference within the data entries.

For pressure switches the source with the most failures, source C, also represents the oldest data (1968 study). Therefore, this data entry was removed. The remaining entries include 4 failures in approximately 74 million hours with a failure rate of 54.2 fits.

For inertial switches, the same data entry (Souce C) was removed and the entries retested. The test indicated no significant differences within the remaining entries. These entries include 12 failures in approximately 181 million hours with a failure rate of 66.4 fits.

Two device types, sensitive and manual rotary S&A, indicated no failures. It is recommended that the "general" category failure rate be used until further data is collected on these devices. The pooled switch data and failure rates are shown in Table 4.1-3. The right hand column in Table 4.1-3 gives the 90% confidence one-sided limit on the failure rate. The true failure rate should lie below this limit with 90% confidence.

TABLE 4.1-3. POOLED SWITCH NON-OPERATING DATA

TYPE	NON-OP. HRS. IN MILLIONS	NO. OF FAILURES	FAILURE RATE IN FITS	90% CONFIDENCE ONE-SIDED FAILURE RATE
General	132.819	11	82.8	125.3
Toggle/ Pushbutton	38.506	1	26.0	101.1
Pressure	73.82	4	54.2	108.4
Thermostatic	58.466	1	17.1	66.6
Sensitive			*	*
Stepping	5.00	2	400.	1064.
Manual Rotary S&A			*	*
Solenoid	82.36	9	109.3	172.7
Motor Driven S&A	65.104	9	138.2	218.5
Inertial	180.629	12	66.4	98.7

*Use "general" failure rate.

4.1.4 Failure Modes

Table 4.1-4 summarizes the failure modes and mechanisms that were identified in the non-operating data. They include corrosion of contacts and other metal surfaces; load relaxation of springs; aging of O-rings, packing, etc., as long term mechanisms. Other mechanisms appear to be manufacture related. The majority of these devices were thoroughly tested before being placed into storage. The manufacture related defects therefore must be marginal problems which escape these tests and are sufficiently stressed in the storage environments to result in failures.

TABLE 4.1-4. REPORTED FAILURE MODES & MECHANISMS IN STORAGE

SWITCH TYPE	FAILURE MODES & MECHANISMS
Inertial	Corrosion
Inertial	Mechanism slippage
Inertial	Foreign particle
Inertial	Improper clearance
Inertial	Improperly manufactured cover plate - 2
Inertial	Misaligned gear train
Motor Driven	Swelling, cracking & general materiel degradation of O-rings, packing & insulators
Motor Driven	Corrosion of bearings, contacts, switch parts, gear assemblies & motor armature
Motor Driven	Load relaxation of helical compression springs
Motor Driven	Bonding of friction plate clutch assembly
Pushbutton	Bent leaf spring contact

TABLE 4.1-5. OPERATIONAL FAILURE DISTRIBUTION FOR SWITCHES

Failure Mode	Number of Failures	Percentage
Contamination	5	1
Failed to operate	9	1
Improper adjustment	16	2
Improper operation	16	2
Intermittent operation	72	10
Internal part failure	0	0
Leaking	8	1
Mechanical damage	127	17
Mechanical interference	56	7
Missing or wrong part	0	0
Slow or sluggish operation	0	0
Weak or aging effect	5	1
Arcing	0	0
Drift/unstable/erratic	42	6
Defective contacts	12	2
Open	58	8
Shorted	30	4
Squib failed to fire	79	10
Voltage out of spec	29	4
Dielectric, humidity	0	0
Unknown	190	25
TOTAL	754	

Table 4.1-5 summarizes failure modes of switches in operational environments. This table, taken from data source C, shows the distribution of failures in switches, for those failures which could be identified quantitatively.

4.2 Switches Operational Prediction Model

The MIL-HDBK-217B general failure rate model for switches is:

$$\lambda_p = \lambda_b \ (\Pi_E \times \Pi_C \times \Pi_{cyc}) \times 10^{-6}$$

where: λ_p = device failure rate
λ_b = base failure rate
Π_E = Environmental Adjustment Factor
Π_C = Complexity Adjustment Factor
Π_{cyc} = Cycling Rate Adjustment Factor

The various types of switches require different failure rate models that vary to some degree from the basic model. The specific failure rate model and Π factor values for each group are shown in figures 4.2-1 through 4.2-3.

Figure 4.2-1 contains the model for snap-action toggle or pushbutton switches covered by military specifications MIL-S-3950 and MIL-S-8805.

Figure 4.2-2 contains the model for basic sensitive switches covered by military specification MIL-S-8805.

Figure 4.2-3 contains the model for rotary, ceramic or glass wafer, silver alloy contact switches covered by military specification MIL-S-3786.

The switch models assume the following: the design application is according to the part specification; the device is protected from dust with metal or plastic cases; either ac loads or resistive dc loads are involved; and failure is defined as a drop in contact voltage exceeding specification limits.

FIGURE 4.2-1. MIL-HDBK-217B OPERATIONAL FAILURE RATE PREDICTION MODEL FOR TOGGLE OR PUSHBUTTON (Single Body) SWITCHES

$$\lambda_p = \lambda_b \, (\Pi_E \times \Pi_C \times \Pi_{cyc}) \quad (\text{failure}/10^6 \text{ hours})$$

λ_b (Base Failure Rate)

Description	Normal Conditions			λ_b for ≤ 1 Operation/hr	
	Load		Life		
	Volts	Amps	Operations	MIL-SPEC	Lower
Toggle or Pushbutton:					
Snap Action	6.0 to 120	0.01 to 10	20,000	0.01	0.75
Non-Snap Action	6.0 to 32	0.01 to 1.0	20,000	0.04	0.60

Π_C (Contact Form & Quantity Factor)

Contact Form and Quantity	Π_C
SPST	1.0
DPST	1.5
SPDT	1.75
3PST	2.0
4PST	2.5
DPDT	3.0
3PDT	4.25
4PDT	5.5
6PDT	8.0

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	0.3
Space Flight	0.3
Ground, Fixed	1.0
Airborne, Inhabited	12.0
Naval, Sheltered	1.2
Ground, Mobile	5.0
Naval, Unsheltered	7.0
Airborne, Uninhab.	15.0
Missile, Launch	200.0

Π_{cyc} (Cycling Rates Factor)

Switching Cycles per Hr (cyc)	Π_{cyc}
$\leq$ 1 cyc/hr	1.0
> 1 cyc/hr	cyc/hr
For a cycling rate greater than 1.0 cycle per hr, Π_{cyc} is equal to the cycling rate/hr.	

FIGURE 4.2-2. MIL-HDBK-217B OPERATIONAL FAILURE RATE PREDICTION MODEL FOR ROTARY (Wafer) SWITCHES

$$\lambda_p = \lambda_b \left(\Pi_E \times \Pi_{cyc}\right) \text{ (failures/}10^6\text{ hours)}$$

(Base failure rate model) $\lambda_b = \lambda_{bF} + n\lambda_{bF}$ or $\lambda_{bE} + n\lambda_{bG}$

Description	Normal Conditions			Base Failure Rate λ_b, for ≤ 1 operation/hr (failures/10^6 hrs)		
	Load		Life			
	Volts	Amps	Operations			
Actuation Assembly	-	-	-	$\lambda_{bE} = 0.4$		
Rotary Switch Wafers:					MIL. SPEC.	LWR. QUAL.
Ceramic RF Wafers	10 to 6.0	10 to 0.25	20,000	λ_{bF}	0.002	0.08
Medium-Power Wafers	6.0 to 120	0.01 to 10	20,000	λ_{bG}	0.002	0.24
n = number of contacts						

Π_{cyc} (Cycling Factor)

Switching Cycles per Hr (cyc)	Π_{cyc}
≤ 1 cyc/hr	1.0
> 1 cyc/hr	cyc/hr
For a cycling rate greater than 1.0 cycle per hr, Π_{cyc} is equal to the cycling rate/hr.	

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	0.3
Space Flight	0.3
Ground, Fixed	1.0
Airborne, Inhabited	12.0
Naval, Sheltered	1.2
Ground, Mobile	5.0
Naval, Unsheltered	7.0
Airborne, Uninhab.	15.0
Missile, Launch	200.0

FIGURE 4.2-3. MIL-HDBK-217B OPERATIONAL FAILURE RATE PREDICTION MODEL FOR BASIC SENSITIVE SWITCHES

$$\lambda_p = \lambda_b \ (\pi_E \times \pi_{cyc}) \ \text{(failures/10}^6\text{hours)}$$

Base failure rate model $\lambda_b = \lambda_{bE} + n\lambda_{bC}$ or $\lambda_{bE} + n\lambda_{bD}$

Description	Normal Conditions			Base Failure Rate, λ_b, for ≤ 1 operation/hr (failures/10^6 hours)		
	Load		Life			
	Volts	Amps	Operations		MIL Spec	Lwr. Qual.
Basic Sensitive Switch:						
Actuation Differential >0.002 in.	6.0 to 120	0.01 to 5.0	100,000	λ_{bC}	.0035	1.80
Actuation Differential <0.002 in.	6.0 to 60	0.01 to 1.0	100,000	λ_{bD}	.007	4.9
Actuation Assembly	-	-	-	λ_{bE}	0.4	0.4
n = number of contacts or active poles.						

π_{cyc} (Cycling Rates Factor)

Switching Cycles per Hr (cyc)	π_{cyc}
$\leq$ 1 cyc/hr	1.0
> 1 cyc/hr	cyc/hr
For a cycling rate greater than 1.0 cycle per hr, π_{cyc} is equal to the cycling rate/hr.	

π_E (Environmental Factor)

Environment	π_E
Ground, Benign	0.3
Space Flight	0.3
Ground, Fixed	1.0
Airborne, Inhabited	12.0
Naval, Sheltered	1.2
Ground, Mobile	5.0
Naval, Unsheltered	7.0
Airborne, Uninhab.	15.0
Missile, Launch	200.0

4.3 Operational/Non-Operational Failure Rate Comparisons

4.3.1 Sample Calculations from MIL-HDBK-217B

From these models minimum operation failure rates are found below. A fixed ground environment is assumed, corresponding to storage with uncontrolled temperature and humidity.

For a snap-action switch of MIL specification quality, $\lambda_b = 0.01$, fixed ground environment, $\Pi_E = 1.0$, SPST contacts, $\Pi_C = 1.0$, and switching rate less than once per hour, $\Pi_{cyc} = 1.0$. The resulting failure rate for this switch is 0.010 f/Mhr, or 10 fit.

For a sensitive switch, actuation greater than 0.002 inches, MIL specification quality, $\lambda_{bc} = 0.0035$, fixed ground environment, $\Pi_E = 1.0$, switching rate less than once per hour, $\Pi_{cyc} = 1.0$, one contact.* The resulting failure rate for this switch is 0.404 f/Mhr, or 404 fit.

For a rotary switch, MIL specification quality, $\lambda_{bc} = 0.0035$, fixed ground environment, $\Pi_E = 1.0$, switching rate less than once per hour, $\Pi_{cyc} = 1.0$, two contacts.* The resulting failure rate for this switch is 0.404 f/Mhr, or 404 fit.

4.3.2 Operational Failure Rates

Operational failure rates for types of switches covered by the MIL-HDBK-217B model are shown as part of Table 4.3-1.

Operational failure rate data for switches was extracted from report RADC-TR-74-268, Revision of RADC Nonelectronic Reliability Notebook, D. F. Cottrell, et al, Martin Marietta Aerospace, dated October 1974. This data is shown in Tables 4.3-2 through 4.3-9 and compared with the non-operating failure rate prediction.

4.3.3 Comparison of Operational and Storage Failure Rates

Tables 4.3-1 and 4.3-9 show the comparison between the operational failure rates and the storage failure rates. The MIL-HDBK-217B comparison indicates a higher failure rate in storage than in operation for toggle switches. For rotary and sensitive switches, the non-operating to operating ratio is 1:5.

Comparing the common environment (ground) in the other data source, the non-operating to operating ratio ranges from 1:9 for the general category of switches to 1:147 for thermostatic switches.

TABLE 4.3-1. OPERATIONAL FAILURE RATES BASED ON MIL-HDBK-217B

SWITCH TYPE	GROUND FIXED ENVIRONMENT λ IN FITS	RATIO OPERATING/ NON-OPERATING
Toggle	10	.4
Sensitive	404	5.
Relay	404	5.

TABLE 4.3-2. OPERATIONAL/NON-OPERATIONAL RELIABILITY COMPARISON - SWITCHES, GENERAL

	PART HRS. (10^6)	NO. OF FAILURES	FAILURE RATE IN FITS	$\lambda_{op}/\lambda_{no}$
Environment				
Non-Operating				
Ground, Fixed	132.819	11	82.8	-
Operating				
Satellite	7.880	4	507.6	6.
Ground	1.347	0	(<742.4)	9.
Airborne	10.279	1100	107014.	1292.
Helicopter	3.528	348	98639.	1191.
Submarine	3.952	2	506.1	6.

TABLE 4.3-3. OPERATIONAL/NON-OPERATIONAL RELIABILITY COMPARISON - SWITCHES, PRESSURE

	PART HRS. (10^6)	NO. OF FAILURES	FAILURE RATE IN FITS	$\lambda_{op}/\lambda_{no}$
Environment				
Non-Operating				
Ground, Fixed	73.82	4	54.2	-
Operating				
Ground	47.741	100	2095.	39
Ground, Mobile	17.184	105	6110.	113
Airborne	34.425	1929	56035.	1034
Helicopter	1.047	348	332378.	6132
Submarine	.613	4	6525.	120
Shipboard	.798	18	22556.	416

TABLE 4.3-4. OPERATIONAL/NON-OPERATIONAL RELIABILITY COMPARISON - SWITCHES, PUSHBUTTON

	PART HRS. (10^6)	NO. OF FAILURES	FAILURE RATE IN FITS	$\lambda_{op}/\lambda_{no}$
Environment				
Non-Operating				
Ground, Fixed	38.506	1	26.0	-
Operating				
Ground	22.184	6	270.5	10.
Airborne	3.624	101	27870.	1072.
Helicopter	1.286	0	(<777.6)	30.
Submarine	89.879	7	77.9	3.
Shipboard	120.156	55	457.7	18.

TABLE 4.3-5. OPERATIONAL/NON-OPERATIONAL RELIABILITY COMPARISON - SWITCHES, ROTARY

	PART HRS. (10^6)	NO. OF FAILURES	FAILURE RATE IN FITS	$\lambda_{op}/\lambda_{no}$
Environment				
Non-Operating				
Ground, Fixed	-	-	82.8	-
Operating				
Satellite	2.391	1	418.2	5
Ground	36.108	48	1329.	16
Airborne	14.749	261	17696.	214
Helicopter	.092	2	21739.	263
Submarine	20.204	32	1584.	19
Shipboard	52.097	80	1536.	19

TABLE 4.3-6. OPERATIONAL/NON-OPERATIONAL RELIABILITY COMPARISON - SWITCHES, SENSITIVE

	PART HRS. (10^6)	NO. OF FAILURES	FAILURE RATE IN FITS	$\lambda_{op}/\lambda_{no}$
Environment				
Non-Operating				
Ground, Fixed	-	-	82.8	-
Operating				
Ground	11.472	13	1133.	14.
Airborne	12.560	184	14650.	177.
Helicopter	.610	3	4918.	59.
Submarine	45.927	51	1110.	13.
Missile	.008	2	250000.	3019.

TABLE 4.3-7. OPERATIONAL/NON-OPERATIONAL RELIABILITY COMPARISON - SWITCHES, STEPPING

	PART HRS. (10^6)	NO. OF FAILURES	FAILURE RATE IN FITS	$\lambda_{op}/\lambda_{no}$
Environment				
Non-Operating				
Ground, Fixed	5.00	2	400.	-
Operating				
Submarine	.234	5	21368.	53.

TABLE 4.3-8. OPERATIONAL/NON-OPERATIONAL RELIABILITY COMPARISON - SWITCHES, THERMOSTATIC

	PART HRS. (10^6)	NO. OF FAILURES	FAILURE RATE IN FITS	$\lambda_{op}/\lambda_{no}$
Environment				
Non-Operating				
Ground, Fixed	58.466	1	17.1	-
Operating				
Ground	4.381	11	2511.	147.
Airborne	6.733	44	6535.	382.
Helicopter	.218	9	41284.	2414.
Submarine	1.838	7	3808.	223.
Shipboard	45.767	29	633.6	37.

TABLE 4.3-9. OPERATIONAL/NON-OPERATIONAL RELIABILITY COMPARISON - SWITCHES, TOGGLE

Environment	PART HRS. (10^6)	NO. OF FAILURES	FAILURE RATE IN FITS	$\lambda_{op}/\lambda_{no}$
Non-Operating				
Ground, Fixed	38.506	1	26.0	-
Operating				
Ground	237.545	135	568.3	22.
Ground,Mobile	.359	1	2786.	107.
Airborne	35.446	255	7194.	277.
Helicopter	.430	8	18605.	716.
Shipboard	141.438	67	474.	18.

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5.0 Relays

The term relay implies that the voltage interrupted at the contacts is not high, i.e., not over 300 volts. Devices which interrupt high voltages are termed contactors or circuit breakers, and have special arrangments for extinguishing the arc.

Common electromagnetic relay construction includes the contacts, pigtail, armature, springs, magnetic core and coil.

Contacts have three functions which should be distinguished, namely, making, breaking, and carrying the load current. Making current may be several times the load current.

Where possible, contacts are designed to have snap-action, which means that the contacts are under a positive pressure when closed, and separated by a definite distance when open.

Where current must be brought to a movable contact, a soft copper stranded wire wound in a spring shape called a pigtail is often used. The use of a pigtail can be avoided by using a double movable contact which bridges a pair of stationary contacts.

The inertia of the armature is a significant factor in the opening and closing rate. For resistance to shock and vibration, the armature is made symmetrical about the hinge, so that torques are not produced about the hinge by linear accelerations.

The retract spring supplies all of the contact force for the normally closed contacts, and also tends to prevent shock and vibration from disturbing the contacts. The opening force is partly from the retract spring, but primarily from the contact spring.

A great variety of special features and construction are available. Latching and time delay are common features, and the reed construction has advantages for some applications.

Besides the electromagnetic relay considered here, a large class of devices can perform the relay function. These are called static relays, because they do not have the moving contacts of the electromagnetic relay. The term static relay includes several types of device, such as photoconductors, silicon controlled rectifiers, vacuum tubes, magnetic amplifiers, and transistors. An equivalent exists based on each of these devices.

Fluidic devices are able to perform logic and switching, and the input sensors and output drives can often be designed to use the same fluid power supply. Response times on the order of one millisecond are typical, and radiation hardening is not a problem.

Snap action requires either regenerative elements, such as the controlled rectifier, the unijunction, the four layer diode, and the tunnel diode; or regnerative circuitry, such as the blocking oscillator, the Schmitt trigger, and the bistable multivibrator.

In general, to attain specific features such as isolation or suppression of voltage spikes in a static circuit requires additional complexity. Most of the static devices are very fast compared to electromagnetic relays, which usually require a few milliseconds to transfer. Saturable core devices are comparatively slow, however, the fastest response being a half cycle of the drive frequency, typically 1000 hertz or less. Multipole switching with static devices generally requires duplication of the output circuitry. There is usually some consumption of power in both states of a static switch.

5.1 Storage Reliability Analysis

5.1.1 Failure Mechanisms

There was no storage failure mode information in the available data. The commonest operational failure mode is open or intermittent contacts caused by contamination, usually particulate, of the contacts. Sticking contacts is the next most common operational failure mode, and is caused by either hot or cold welding.

5.1.1.1 Contact Problems

A number of phenomena take place at the contacts, some of which tend to provide a wearout mechanism in the reliability sense. A common life expectancy is one million operations, but the dry reed types run to 500 million, and mercury wetted types above that.

5.1.1.1.1 Current Carrying

A metal exposed to air will quickly be covered with a film of oxide or adsorbed oxygen. If the film is thick, it will be practically insulating; if thin, it will be permeable to electrons by means of the tunnel effect.

When two such metal surfaces are pressed together, only a portion of the surfaces carries the mechanical load. Because of the surface roughness of even polished surfaces, there will be small regions of plastic deformation as well as larger regions of elastic deformation. In parts of the regions of plastic deformation the surface film will be separated and metal-to-metal contact will occur. These isolated spots account for most of the electrical conductivity of the contact. These spots are always cold-welded, but the elastic forces help to break the weld on opening. The influence of the surface films in limiting cold welding and friction is desirable, and lubrication may be added to electrical contacts for this purpose. For the same reason, oxygen should be present if the contacts are within a sealed enclosure.

If more than a few volts are applied, another mechanism, called fritting, creates metal-to-metal contact. Fritting is a result of metallic ion migration due to electrostatic fields at the metal-film interface. It can both expand existing contact spots and create new ones.

Because the equations for heat conduction and for electrical conduction are similar, there is a fixed relation between the voltage drop across a contact and the maximum temperature attained within it. Table 5.1-1 shows values for some common contact materials. Softening refers to annealing, which takes place below the melting point. The required voltages are quite low, so that the corresponding phenomena can be expected in most practical circuits. A "dry" circuit is one in which the voltages are too low for any of these phenomena.

Table 5.1-1. Critical Voltages for Some Common Contact Materials

MATERIAL		SOFTENING VOLTAGE	MELTING VOLTAGE	BOILING VOLTAGE
Ag	Silver	0.09	0.37	0.75
Au	Gold	0.08	0.43	0.9
Cu	Copper	0.12	0.48	0.8
Pt	Platinum	0.25	0.71	1.3
W	Wolfram	0.6	1.1	2.1

5.1.1.1.2 Closing

As the contacts close, the voltage stress rises until the gap breaks down. Thus, there is usually a brief discharge on closing. For 10 volts across the gap, breakdown occurs at about 0.0001 mm in air. There is usually some contact bounce at closure, which can produce arcing and welding. Inrush currents can be far higher than steady state currents, factors of 10 to 20 are not uncommon. Many things can be done to minimize the effects: multiple contacts will prevent an arc forming as long as one of them is closed, cadmium and tungsten are resistant to welding, the mechanism can be designed with leverage to break the welds, and circuit modification is a possibility.

5.1.1.1.3 Opening

There are two major processes of material transfer across the contacts, both occur during the opening process. As the contacts begin to open, a bridge of molten metal is formed, unless the contact voltage is very low. As this bridge is drawn out, it eventually separates. The separation is usually due to boiling of the metal at the hottest point, but sometimes due to surface tension. The heating is usually unsymmetrical so that there is a net transfer of material.

After the bridge breaks, arcing will occur if sufficient voltage and current are available. The requirements are quite low: about 9 volts and under 0.5 ampere, depending somewhat on the material of the contacts and the atmosphere. Arcing is characterized by intense heating of very small spots on the contacts and conduction thru an ionized plasma. Material loss depends on the temperatures attained. Curiously, arcs in air lose much less material than arcs in vacuum; the reason is that the cathode spot is much larger and cooler because the oxygen lowers the work function at the cathode surface. Some materials with a high melting point, notably wolfram (tungsten) and carbon, are able to support an arc without melting, and material loss is thus reduced.

5.1.1.1.4 Contact Materials

The choice of contact material depends on the duty required. Usually both contacts are made of the same material. The use of different materials introduces thermoelectric effects because of the high temperatures at the contact.

For very low voltages and currents, it is important that the contact material be free of corrosion and not form an insulating film. Gold is the most satisfactory material, metals in the platinum group are also used.

For light and moderate duty, silver or a silver alloy is the most satisfactory material. The oxide tarnish, although readily visible, is conducting. (In atmospheres containing suffur, however, a nonconducting sulfide is formed which is a serious problem.) High conductivity of the bulk material, softness, and low melting point, all help to insure a low resistance contact with moderate contact force.

For heavy duty, where arcing is the chief concern, a high melting point is the prime consideration. Wolfram, molybdenum, and carbon are able to sustain an arc without reaching their melting point (sufficient thermionic emission occurs at temperatures below their melting point).

Mercury provides a contact material that is not damaged by arcing. Designs in which the liquid requires a fixed position are not suited for applications where shock and vibration are problems. By using thin films in which surface tension is the dominant force, devices which can be mounted in any position and will withstand moderate acceleration (5 G) in any direction have been constructed. Designs using liquid mercury cannot be used below the freezing point, -40°C.

The common conductors are unsatisfactory as contacts. Copper tends to weld, and is readily damaged by arcing. Aluminum forms a thick, tough insulating film of oxide, and is one of the few metals which creep indefinitely at room temperature, so that it is difficult to maintain contact force.

Table 5.1-2 is a classification of the duty requirements. The terminology is not standardized, despite several attempts, by standardizing bodies, so this digure is illustrative rather than definitive.

5.1.2 Non-Operational Failure Rate

The storage failure rate for all types of relays is 8.5 failures per billion hours. The 90% confidence limit is 17.0 failures per billion hours.

5.1.3 Data Description

Data was received from four sources and three missile programs representing 2085.7 million part non-operating hours with 45 failures reported. Table 5.1-3 summarizes the relay data from each source.

The data in Source A contained data from Source C. A comparison was performed which identified common data between the two sources. Data was removed from Source A to avoid duplication. The hours and failures in parenthesis below Source A data represents total Source A data while the hours and failures listed on the same line represents unique data to Source A.

The data represents a wide variety of devices. Failure rates for individual devices range from 8.7 fits (failures per billion hours) to 637 fits. The overall failure rate is 20.2 fits.

Table 5.1-4 through 5.1-10 presents data from each source identifying the type of relay where available. Each data source is described below.

5.1.3.1 Source A Data

Source A represents a reliability study performed under contract to RADC in 1974. This source identified the type and quality grades for the devices, however, it provided no information regarding storage conditions or individual programs. Data for the device types which are in parenthesis in Table 5.1-4 is a duplication of data from Source C in Table 5.1-6.

Table 5.1-2. CONTACT CLASSIFICATION BY SERVICE REQUIREMENTS

Voltage across contacts (Note 1)	Classification (Note 2)	Dominant mechanism	Typical contact material
0 - 0.5	dry	Surface films are critical	Gold
0.5-2.0	light duty	Bridging takes place, but no arcing	Silver
2.0-10	medium duty	Vaporization takes place, but arcing cannot be sustained	Silver-Cadmium
10-300	heavy duty	Arc can be sustained, but will not reignite	Wolfram
300-up	breaker	Arc must be extinguished by lengthening and cooling	Copper under oil

Note 1: Voltage across contacts is voltage at break. It is influenced by inductance, and so is often larger than the source voltage. Voltage values vary somewhat with the materials used.

Note 2: The terms are widely used, but the definitions given vary.

5.1.3.2 Source B Data

The storage data under Source B actually represents standby data in an orbiting satellite environment. One failure was indicated in 7.46 million relay standby hours.

5.1.3.3 Source C Data

Source C data represents a reliability study performed under contract to RADC in 1968. No environments were provided. For approximately 642 million relay non-operating hours, 20 failures were reported. The data includes non-operating hours on a number of different types of relays. The failures, however, were recorded against relays for which the type was not identified.

5.1.3.4 Source P Data

Source P represents a special aging and surveillance program. Devices are stored in a controlled environment. The data included 42 holding relays stored for an average age of 66 months (the oldest unit was 71 months) and 39 latching relays stored for an average age of 55 months (the oldest unit was 60 months).

One latching relay failed at test age 20 months. No failure analysis was available, however, a retest by the manufacturer could not duplicate the failure.

5.1.3.5 Missile E-1 Data

Missile E-1 data consists of 874 missiles stored for 20 months. The missiles were stored in containers exposed to external environmental conditions in the northeast U. S. They were also transported once from coast to coast. The data included three types of relays: DPDT, rotary motor and thermal. Two failures were recorded on the rotary motor relays.

5.1.3.6 Missile G Data

Missile G data consists of 39 missiles stored for periods from 28 months to 56 months for an average storage period of 39 months. The missiles in storage containers experienced the following environments: 12 missiles stored outside in the southeast desert; 12 missiles stored outside in the northeast

U. S.; 12 missiles stored on the Gulf Coast; and 23 missiles stored in bunkers in the southeast U. S. No failures were recorded for the armature relays.

5.1.3.7 Missile I Data

Missile I data consists of 2,070 missiles stored for periods from 1 month to 40 months for an average storage period of 14 months. Approximately 80 percent of the missiles were stored in U. S. depots while the remainder were stored at various bases around the country. Two failures were recorded in armature relays at test age 8 months and age 12 months.

TABLE 5.1-3. NON-OPERATING DATA SUMMARY

SOURCE	MILLION PART NON-OPER. HRS.	NO. OF FAILURES	FAILURE RATE IN FITS
A	165.793	0	(<6.0)
	(797.111)	(19)	
B	7.46	1	134.0
C	642.109	20	31.1
P	3.59	1	278.6
MISSILE			
E-1	382.812	2	5.2
G	4.5	0	(<222.2)
I	82.36	2	24.3
TOTALS	1288.624	26	20.2
	(2085.734)	(45)	

TABLE 5.1-4. SOURCE A DATA

DEVICE TYPE	NON-OPER. HRS. IN MILLIONS	NO. OF FAILURES	FAILURE RATE IN FITS
(General)	(587.4)	(19)	(32.3)
General, Sub	144.1	0	(<6.9)
(Crystal Can, Latching)	(43.46)	(0)	(<23.0)
Latching, Gen.	12.33	0	(<81.1)
(Thermal)	(0.458)	(0)	(<2183.)
Non-Latching, General	9.363	0	(<107.)

TABLE 5.1-5. SOURCE B DATA

DEVICE TYPE	NO. OF DEVICES	NON-OPER. HRS. IN MILLIONS	NO. OF FAILURES	FAILURE RATE IN FITS
-	1912	7.46	1	134.0

TABLE 5.1-6. SOURCE C NON-OPERATING DATA

DEVICE TYPE	NON-OPER. HRS. IN MILLIONS	NO. OF FAILURES	FAILURE RATE IN FITS
Microminiature	.1168	0	(<8562)
Miniature	.7244	0	(<1380)
Rotary	.164	0	(<6098)
Solenoid	.370	0	(<2703)
Sw.- 2 pole	.318	0	(<3145)
Thermal	.458	0	(<2183)
Goldplated-4 pole	79.0	0	(<12.7)
Armature	.322	0	(<3106)
"	.0658	0	(<15198)
"	.8510	0	(<1175)
"	1.2604	0	(<793)
"	.3699	0	(<2703)
"	9.6177	0	(<104)
"	5.1564	0	(<194)
"	2.6460	0	(<378)
"	1.8096	0	(<535)
Crystal Can	1.0562	0	(<947)
" "	9.9152	0	(<101)
" "	1.0168	0	(<983)
" "	2.6577	0	(<376)
" "	27.872	0	(<36)
" "	.0728	0	(<13736)
" "	.8792	0	(<1137)
-	1.85	0	(<541)
-	12.576	0	(<80)
-	3.050	0	(<328)
-	37.688	0	(<27)
-	12.207	0	(<82)
-	128.	3	23.4
-	281.	15	53.4
-	9.982	1	100.2
-	8.976	1	111.4

TABLE 5.1-7. SOURCE P DATA

DEVICE TYPE	NO. OF DEVICES	NON-OPER. HRS. IN MILLIONS	NO. OF FAILURES	FAILURE RATE IN FITS
Holding	42	2.02	0	(<495)
Latching	39	1.57	1	637.

TABLE 5.1-8. MISSILE E-1 DATA

DEVICE TYPE	NO. OF DEVICES	NON-OPER. HRS. IN MILLIONS	NO. OF FAILURES	FAILURE RATE IN FITS
DPDT	6118	89.323	0	(<11.)
Rotary Motor	15732	229.687	2	8.7
Thermal	4370	63.802	0	(<16.)

TABLE 5.1-9. MISSILE G DATA

DEVICE TYPE	NO. OF DEVICES	NON-OPER. HRS. IN MILLIONS	NO. OF FAILURES	FAILURE RATE IN FITS
Armature	156	4.5	0	(<222)

TABLE 5.1-10. MISSILE I DATA

DEVICE TYPE	NO. OF DEVICES	NON-OPER. HRS. IN MILLIONS	NO. OF FAILURES	FAILURE RATE IN FITS
-	2070	20.59	0	(<49.)
Armature	6210	61.77	2	32.

5.1.4 Data Evaluation

The data from the various sources was combined by device type. Only three relay types plus the general category reported failures. The resulting failure rates range from 8.7 fits for rotary relays with two failures reported to 71.9 fits for latching relays with one failure reported.

Since the failure rates by device type represent a very small number of failures except for the general category a test of significance (described in Appendix A) was performed to test whether a single failure rate could describe all the relay types that showed failures. The test indicated that there was no significant difference. The combined data for all relay types showing failures including the "general" type represents 833.4 non-operating hours with 26 failures giving a pooled failure rate of 31.2 fits.

Next a test was performed to pool all relay data (including 0 failure data) into a single general relay category. This test indicated there was a significant difference when the 0 failure cases were included.

Since the failure data by device type was insufficient to determine differences. The data was broken out again by source and regrouped. All relay data from missile programs were placed in one group and the other sources into a second group. These pooled data groups were tested and no significant differences were measured within the groups. The pooled data is shown in Table 5.1-12.

In Table 5.1-12 the data under group 1 gives a failure rate of 26.9 fits with a 90% confidence that the true failure rate is below 35.7 fits. Group 2 gives a failure rate of 8.5 fits with a 90% confidence that the true failure rate is below 17.0 fits.

The missile sources represent newer devices than the other sources. Until sufficient data becomes available to distinguish between relay types, it is recommended that the non-operating failure rate of 8.5 fits be used to represent the best case for a "general" relay category within the current state-of-the-art.

TABLE 5.1-11. NON-OPERATING DATA BY RELAY TYPE

TYPE	NON-OPERATING STORAGE HRS. IN MILLIONS	FAILURES	FAILURE RATE IN FITS
General	523.379	21	40.1
General, Sub	144.1	0	(<6.9)
Latching, Gen.	13.9	1	71.9
Non-Latching, Gen	9.363	0	(<106.8)
Microminiature	.1168	0	(<8561.6)
Miniature	.7244	0	(<1380.5)
Rotary	229.851	2	8.7
Solenoid	.370	0	(<2702.7)
Sw. - 2 pole	.318	0	(<3444.7)
Thermal	64.260	0	(<15.6)
Goldplated 4 pole	79.0	0	(<12.7)
Armature	22.1588	0	(<45.1)
Crystal Can	43.4699	0	(<23.0)
Holding	2.02	0	(<495.0)
DPDT	89.323	0	(<11.2)
Armature	66.27	2	30.2

TABLE 5.1-12. POOLED DATA GROUPS

GROUP 1

SOURCE	NON-OPER. HRS. IN MILLIONS	NO. OF FAILURES	FAILURE RATE IN FITS
A	165.763	0	(<6.0)
B	7.46	1	134.0
C	642.109	20	31.1
P	3.59	1	278.6
TOTALS	818.952	22	26.9

GROUP 2

MISSILE	NON-OPER. HRS. IN MILLIONS	NO. OF FAILURES	FAILURE RATE IN FITS
E-1	382.812	2	5.2
G	4.5	0	(<222.2)
I	82.36	2	24.3
TOTALS	469.672	4	8.5

5.2 Relay Operational Failure Rate Model

The MIL-HDBK-217B failures rate model for relays is:

$$\lambda_p = \lambda_b \, (\Pi_E \times \Pi_C \times \Pi_{cyc} \times \Pi_F) \times 10^{-6}$$

$$\lambda_b = \lambda_T \, (\Pi_L)$$

where: λ_p = device failure rate

λ_b = base failure rate

Π_E = Environmental Adjustment Factor

Π_C = Complexity Adjustment Factor

Π_{cyc} = Cycling Rate Adjustment Factor

Π_F = Application and Construction Adjustment Factor

λ_T = Base Temperature Failure Rate

Π_L = Load Type and Stress Adjustment Factor

Figure 5.2-1 presents the relay model with values for the failure rate and adjustment factors. The model applies to devices covered under the following specifications: MIL-R-5757; MIL-R-6106; MIL-R-19523; MIL-R-39016; MIL-R-19648; MIL-R-83725; and MIL-R-83726.

The base failure rate and adjustment factor values are based on certain assumptions. Refer to the following sections for a description of these parameters.

5.2.1 Base Failure Rate (λ_b)

The equation for the base failure rate, λ_b, is:

$$\lambda_b = \lambda_T \, (\Pi_L)$$

where $\lambda_T = Ae^x$ and $\Pi_L = e^Y$

where $x = \left(\frac{T + 273}{N_T}\right)^G$ $y = \left(\frac{S}{N_S}\right)^H$

T = ambient operating temperature in °C.

S = operating load current/rated resistive load current

e = natural logarithm base, 2.718

A, N_T, N_S, G and H are model constants

The values for the constant parameters are shown in Table 5.2-1. The resulting values of λ_T and Π_L are presented in Figure 5.2-1.

TABLE 5.2-1. RELAY BASE FAILURE RATE MODEL CONSTANTS

Constants	λ_T (85°C)	λ_T (125°C)	Π_L (Lamp)	Π_L (Ind)	Π_L (Res)
A	5.55×10^{-3}	5.4×10^{-3}	-	-	-
N_T	352.0	377.0	-	-	-
N_S	-	-	0.20	0.40	0.80
G	15.7	10.4	-	-	-
H	-	-	2.0	2.0	2.0

5.2.2 Π Adjustment Factors

5.2.2.1 Environmental Adjustment Factor, Π_E

Π_E accounts for the influence of environmental factors other than temperature. Refer to the environment description in Appendix

5.2.2.2 Complexity Adjustment Factor, Π_C

Π_C accounts for the contact form and the number of contacts in the relay. The factor applies to active conducting contacts.

5.2.2.3 Cycling Rate Adjustment Factor, Π_{cyc}

Π_{cyc} modifies the model for the rate of cycling.

The value of Π_{cyc} is not valid when relays are used at cycling rates beyond their basic design limits. For example, above 100 cycles per hour a power contactor may overheat; or attempting to operate a general-purpose relay above 10 cycles per second may deform the mechanical motion so that normal wiping action cannot take place and intermittent missing may result.

5.2.2.4 Application and Construction Adjustment Factor, Π_F

Π_F adjusts model for influence of family types and application.

FIGURE 5.2-1 MIL-HDBK-217B OPERATIONAL FAILURE RATE PREDICTION MODEL FOR RELAYS

$$\lambda_p = \lambda_T \; (\pi_L x \pi_E x \pi_C x \pi_{CYC} x \pi_F) \; (\text{FAILURES}/10^6 \text{ HOURS})$$

λ_T (Relay Failure Rate)

	Temp. Rating	
T(°C)	85°C	125°C
25	[illegible]	.0059
30	[illegible]	.0061
40	.0065	.0063
50	.0072	.0066
60	.0085	.0071
70	.011	.0079
75	.013	.0084
80	.016	.0090
85	.021	.0097
90		.011
95		.012
100		.013
105		.015
110		.018
115		.021
120		.025
125		.031

π_L (Load Type & Stress Ratio)

	Load Type		
S	Resistive	Inductive	Lamp
0.05	[illegible]	1.02	1.06
0.1	1.02	1.07	1.28
0.2	1.06	1.28	2.72
0.3	1.15	1.76	9.49
0.4	1.28	2.72	54.6
0.5	1.48	4.77	
0.6	1.76	9.49	
0.7	2.15	21.4	
0.8	2.72		
0.9	3.55		
1.0	4.77		

Note:

$$S = \frac{\text{Operating Load current}}{\text{Rated Resistive Load Current}}$$

π_E (Environment Factor)

Environment	Mil Spec	Lower
Ground, Benign	1.0	2.0
Space Flight	1.0	2.0
Ground Fixed	2.0	4.0
Airborne, Inhabited	8.0	16.0
Naval, Sheltered	9.0	24.0
Ground, Mobile	10.0	30.0
Airborne, Uninhabited	12.0	30.0
Naval, Unsheltered	11.0	30.0
Satellite or Missile Launch	300.0	300.0

π_C (Contact Form and Quantity Factor)

Contact Form & Quantity	π_C
SPST	1.0
DPST	1.5
SPDT	1.75
3PST	2.0
4PST	2.5
DPDT	3.0
3PDT	4.25
4PDT	5.5
6PDT	8.0

π_{CYC} (Cycling Rates Factor)

Mil-Spec Quality		Lower Quality	
Cycles/hr[1]	π_{CYC}	Cycles/hr[1]	π_{CYC}
>1000	$\frac{\text{cycles per hour}}{10}$	>1000	$\left(\frac{\text{cycles per hour}}{100}\right)^2$
1-1000	$\frac{\text{cycles per hour}}{10}$	10-1000	$\frac{\text{cycles per hour}}{10}$
<1	0.1	<10	1.0

π_F (Relay Application and Construction Type Factor)

See Next Page

[1] For sporadic usage, (cycles/hr) is maximum hourly rate;
For fixed rate, (cycles/hr) is average hourly rate;
For cycling distribution in time which obeys a random Poisson process (is also average hourly rate).

FIGURE 5.2-1 MIL-HDBK-217B OPERATIONAL FAILURE RATE PREDICTION MODEL FOR RELAYS (continued)

π_F for Relay Application and Construction Type

Contact Rating	Application Type	Construction Type	π_F MIL-SPEC Quality	π_F LOWER Quality
Signal Current (low mv and ma)	Dry Circuit	Armature (Long)	4	12
		Dry Reed	2	6
		Mercury Wetted	1	3
		Magnetic Latching	6	12
		Balanced Armature	7	14
		Solenoid	7	14
0-5 amp	General Purpose	Armature (Long)	3	6
		Balanced Armature	5	10
		Solenoid	6	12
	Sensitive (0-100 mw)	Armature (Long and short)	5	15
		Mercury Wetted	2	6
		Magnetic Latching	8	20
		Meter Movement	100	100
		Balanced Armature	10	30
	Polarized	Armature (Short)	10	30
		Meter Movement	100	100
	Vibrating Reed	Dry Reed	2	6
		Mercury Wetted	1	3
	High Speed	Armature (Balanced and short)	25	NA
		Dry Reed	2	NA
	Thermal Time Delay	Bimetal	50	100
	Electronic Time Delay Non-Thermal		9	12
	Latching (magnetic)	Dry Reed	10	20
		Mercury Wetted	5	10
		Balanced Armature	5	10
5-20 amp	High Voltage	Vacuum (Glass)	20	40
		Vacuum (Ceramic)	10	20
5-20 amp	Medium Power	Armature (Long and short)	3	9
		Mercury Wetted	1	3
		Magnetic Latching	2	6
		Mechanical Latching	3	9
		Balanced Armature	2	6
		Solenoid	2	6
25-600 amp	Contactors (High Current)	Armature (Short)	7	14
		Mechanical Latching	12	24
		Balanced Armature	10	20
		Solenoid	5	10

5.3 Operational/Non-Operational Failure Rate Comparisons

5.3.1 Sample Operational Failure Rate Calculation

From the model in Section 5.2, the lowest comparable operational failure rate for a relay is calculated below for comparison to the storage condition.

The assumed relay is rated for 125°C and operated at 25°C, $\lambda_T = 0.0059$. The load is resistive, and the load current is 0.05 times rated, $\Pi_T = 1.00$. The relay is MIL specification quality and is operated in a ground fixed environment, $\Pi_E = 2.0$. (The environment is taken as ground fixed to be comparable to field storage where temperature and humidity are not controlled.) Contacts are SPST, $\Pi_C = 1.0$. Cycling rate is less than once per hour, $\Pi_{CYC} = 0.1$. Application is medium power and construction is mercury wetted, $\Pi_F = 1$. For this relay, the predicted failure rate is 0.0012 failures per million hours, or 1.2 fit.

5.3.2 Comparison of Storage and Operational Failure Rates

The failure rate predicted by the model of Section 5.2 is lower than the storage failure rate. There are several possible explanations for this situation: (1) the storage data are not sufficient to justify calculation of failure rates for specific types, so that a suitable comparison is not possible, (2) Occasional operation serves to break down contact film, so that the operational failure rate may actually be less than the storage failure rate for some relay types. (This should not apply to the mercury-wetted type of the sample calculation, however.) (3) In seeking the lowest comparable failure rate, the model of Section 5.2 may have been extrapolated beyond its supporting data.

GIDEP data shows an average operating failure rate of 28 fit for relays in a laboratory environment. GIDEP reports an average failure rate of 3393 fit for a shipboard, exterior deck environment, the only other relay environment for which there was sufficient data to report an average.

Operational failure rate data for relays was extracted from report RADC-TR-74-268, Revision of RADC Nonelectronic Reliability Notebook, D. F. Cottrell, et al, Martin Marietta Aerospace, dated October 1974. This data is shown in Table 5.3-1 and compared with the non-operating failure rate prediction. Comparing the common environment (ground) indicates a non-operating to operating ratio of 1:20.

TABLE 5.3-1. OPERATIONAL/NON-OPERATIONAL RELIABILITY COMPARISON

ENVIRONMENT	PART HOURS (10^6)	NO. OF FAILURES	FAILURE RATE IN FITS	$\lambda_{op}/\lambda_{no}$
Non-Operating				
Ground, Fixed	469.672	4	8.5	-
Operating				
Satellite	118.835	1	8.4	1.
Ground	78.261	13	166.	20.
Airborne	8.602	58	6743.	793.
Helicopter	2.531	157	62031.	7298.
Shipboard	22.552	17	754.	89.
Submarine	43.031	55	1278.	150.

5.4 The Role of Oxygen in the Atmosphere of Relay Contacts

It has become common practice to enclose switch and relay contacts within an hermetically sealed case. The use of a chemically inert atmosphere turns out to be disadvantageous. Oxygen in substantial proportion is desirable for two reasons, both related to the formation of a film at the contact surface. One is that the film acts as a lubricant, preventing sticking of the contacts; the other is that the film substantially reduces damage to the cathode from arcing.

Holm* describes several experiments on adhesion at pages 155-157. (The terms adhesion, sticking, and cold welding refer to the same process.) He describes experiments on arc damage at pages 308-311, see especially figures 56.09 and 56.10. The reduction in loss of contact material is large, a factor of ten or so, but the theoretical explanation for it is not entirely satisfactory. The cathode spot is larger and cooler, and this suggests that the oxygen somehow reduces the work function.

Bates** describes the industry experience with sticking contacts in general terms and gives several case histories. He remarks that dry oxygen is added to the fill gas by several manufacturers in amounts up to 30 percent by volume.

Some current specifications do not permit the use of oxygen in the fill gas. MIL-R-6016F, Relays called for a "suitable inert gas" at Section 3.4.5.2. MIL-R-5757 calls for the "desired inert pressurizing gas" at Section 6.4 (e). MIL-R-19523, MIL-R-19648 and MIL-R-83726 make no mention of the fill gas.

5.5 Storage Recommendations

The field of protective relaying has some close parallels with missile requirements. The purpose there is to prevent damage to power systems. The system is continually monitored by a complex set of relays which are able to distinguish faults both as to time and location, and which disconnects that part of the system when faults occur. Practice in this field has been to inspect and test the protective relays annually.

No applicable storage experience is at hand, but it is suggested on general principles that electromagnetic relays be inspected and operated periodically. The inspection should particularly look for evidence of corrosion, and the operation should test for shorts and opens. Operation under load would not seem to be a requirement.

* "Electric Contacts," Ragnar Holm, Fourth Edition, Springer-Verlag, 1967.

** "Self-Adhesion or Cold Welding of Relay Contacts," C. E. Bates, Proceedings of the 19th Annual Relay Conference, Oklahoma State University, Stillwater, OK, April 1971.

Where the contacts are in a sealed enclosure, the fill gas should include oxygen.

Of possible importance for storage are failure modes due to corrosion. Historically, this has been a problem where fine wire is used for the coil, but sealed construction has overcome it. The coil must have insulation, and there has been some problem due to vapors of organic material from the insulation or potting compound on the contact surface, when the coil and the contacts were sealed into a common enclosure.

Relay design and practice have matured to the point where hardly any storage failures remain to be examined. The only failure in the set of data described in Section 5.1.3 occurred in an operational spacecraft, so it is possible to argue that it should not be counted as a storage failure.

5.6 Reference

The information in Section 5 is a summary of document number LC-78-EM3, "Relay Analysis," dated February 1978. Refer to that document for details of data collection and analysis as well as technical details of relay operation. Some comparative information is taken from MIL-HDBK-217B.

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21. MIL-R-19648 Relay, Time Delay, Thermal, 6 Jan. 1969.

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6.0 Electromechanical Rotating Devices

Electromechanical rotating devices considered in this report include electric motors, generators, synchros and resolvers. Gyros and accelerometers are not included here but are analyzed in reports LC-78-EM1 and LC-78-EM2 respectively.

The rotating devices serve a number of functions in various missile systems. They include control-system applications, power generation, fans and blowers for cooling, antenna spin motors, etc. Control system applications include torque motors in gyro platforms, servo motors, synchros and resolvers.

The action of a dc electric motor results from the reaction between a rotating magnetic field, a permanently situated magnetic field, brushes and commutator. To keep the rotating element, the armature, of a dc motor continually rotating in one direction, current must be passed through the moving conductor at the radian angle opportune to its reaction with a magnetic field flux. Also, this current must be switched off when the required reaction is completed. This switching process is accomplished by brushes and commutator which functionally is a type of rotary switch. Voltage applied to the brushes causes a current to flow through the armature coils which produce a magnetic field. This field seeks to align itself with the permanently located magnetic field and develops a force that causes the armature to turn. The rotation of the armature places different commutator bars under the brushes, which results in a new set of armature coils to be energized and, in turn, causes further rotation of the armature.

For all small dc motors, the armature or rotating element is basically the same, consisting of a laminated iron core, copper wire, and a commutator. The insulated wire is wound in coils distributed around the iron core, and are generally lap wound, each end terminating on a commutator bar. The brushes contact the commutator bars and provide the conductive path from the power supply to the armature coils. The permanently fixed magnetic field is either a permanent magnet or an electromagnet formed by dc current flowing through windings around an iron core field pole.

The construction of the other rotating devices is very like that of the dc electric motors.

AC motors operate on power supplies that reverse polarity cyclically, sinusoidally, and repetitively. AC motors are divided into two main groups - single phase, in which only one ac voltage (or phase) drives the motor; and polyphase, wherein two or more voltages or phases drive the motor. The method of providing starting torque usually defines the motor type. These include shaded-pole motors, capacitor motors and repulsion/induction motors.

A torque motor is one designed premarily to exert torque through a limited travel or in a stalled position. Such a motor may be capable of being stalled continuously or only for a limited time. Torque motors are designed for applications which require prolonged torques or certain special running-torque characteristics. Direct-current, single-phase, or poly-phase induction, repulsion universal, PM, brushless, and other motors can be designed as torque motors. Torque motors of the direct coupled type are used primarily in inertial applications such as stable platforms.

Synchros and resolvers are low speed, low load rotating devices used in a service requiring only slow and infrequent motion. They are used for precise transmission, reception or conversion of angular data. The construction of servos and resolvers is very like that of electric motors, that is, laminated iron stator and rotor with suitable coils placed in slots in the faces, the rotor being mounted on bearings, with slip rings used to power the rotor. The operation is more easily visualized by considering them as variable transformers with voltage ratio dependent on shaft position. An unbalance in the voltages can be used directly to create a torque driving the output shaft to null, or it can be used as the input to a servo system driving the system toward the set point.

A servo motor is basically a two-phase, reversible, ac induction motor which has been modified for servo operation. These operations require fast starts, acceleration, quick stops and reversals, and a nearly linear speed-torque curve and accurate control. A small-diameter, high-resistance rotor helps to give these characteristics. A high torque-to-inertia ratio and a straight-line speed-torque curve are inherhent characteristics of this type motor. Classes include Low Inertia Servomotors for precision, and Viscous Damped Servomotors which provide greater damping than is available through the technique of reducing the no-load speed.

6.1 Storage Reliability Analysis

6.1.1 Non-Operating Failure Rates

Predicted non-operating failure rates for various device types are given in Table 6.1-1. Also included is the 90% confidence limit. The true failure rate should lie below this limit with 90% confidence. For switches showing failures, a range of failure rates from 78.4 to 4702 fits was observe.

TABLE 6.1-1. ROTATING DEVICES NON-OPERATING FAILURE RATES

TYPE	FAILURE RATE IN FITS*	90% CONFIDENCE LIMIT
AC Generator	795.5	1203.
Slip Ring Assy.	120.1	277.
Torquer Motor	308.8	[illegible]45.
Resolvers & Synchros	140.9	[illegible]75.
AC Motor	431.6	1679.
DC Motor	34.4	77.
Blowers & Fans	36.1	83.

6.1.2 Data Description

Non-operating data was available on rotating devices from three sources and two missile programs. The data shown in Table 6.1-2 represents 190.5 million part storage hours with 31 failures reported. The overall failure rate for all the devices is 162.7 fits (failures per billion hours). The failure rates range from 78.4 fits to 4702 fits. A number of types and applications are included in the data.

Each data source is described below.

6.1.2.1 Source A Data

Source A represents a reliability study performed under contract to RADC in 1974. This source identified the type and quality grades for the devides, however, it provided no information regarding storage conditions or individual programs. The types of rotating devices in the data included: dc motors, torque motors, ac generators resolvers, blowers and fans. The following failures were reported: one ac motor, eleven ac generators, and two resolvers. No details on these failures were available.

6.1.2.2 Source B Data

The storage data under Source B actually represents standby data in an orbiting satellite environment. No failures were indicated in 10 thousand slip ring assembly standby hours. Three failures were reported in 638,000 electric motor standby hours.

6.1.2.3 Source C Data

Source C represents a reliability study performed under contract to RADC in 1968. This data included ac, dc and blower motors with no failures reported.

6.1.2.4 Missile E-1 Data

Missile E-1 data consists of 874 missiles stored for 20 months. The missiles were stored in containers exposed to external environmental conditions in the northeast U. S. They were also transported once from coast to coast. Data was available on a dc motor and an antenna spin motor. No failures were reported at the 20 month test.

6.1.2.5 Missile I Data

Missile I data consists of 2,070 missiles stored for periods from 1 months to 40 months for an average storage period of 14 months. Approximately 80 percent of the missiles were stored in U. S. depots while the remainder were stored at various bases around the country. Two torque motors were on each missile and fourteen failures were reported. The age of the units at failure were as follows: 4 months (2); 5 months (1); 7 months (2); 9 months (1); 10 months (1); 11 months (2); 17 months (1); 18 months (1); 19 months (2); and 32 months (1). The primary failure mode was listed as "shorted brakes." No failure analysis was available and it is not certain whether this represents a storage problem or a test stress problem in the system.

TABLE 6.1-2. NON-OPERATING DATA FOR ROTATING DEVICES

SOURCE	NO. OF DEVICES	MILLION PART HRS.	NO. OF FAILURES	FAILURE RATE IN FITS	COMMENT
A	-	.160	0	(<6250.)	elec. mtr. (Gd) instrumentation
	-	4.158	0	(<240.5)	dc torque motor (Gd)
	-	2.004	1	499.0	2 HP ac mtr.(sub)
	-	13.827	11	795.5	ac generator
	-	14.196	2	140.9	resolver (Gd)
	-	8.316	0	(<120.3)	slip ring assy.
	-	2.21	0	(<452.5)	blower & fan (Gd)
	-	7.260	0	(<137.7)	blower & fan axial (Gd)
	-	.410	0	(<2439.)	blower & fan centrifugal (Gd)
B	75	.638	3	4702.	electric motor
	237	.0097	0	(<103000.)	slip ring assy.
C	-	5.7	0	(<175.4)	dc reversible
	1253	4.65	0	(<215.1)	blower & fan ac missile
	-	.0038	0	(<263000.)	ac motor
	-	.149	0	(<6711.)	ac motor
	-	4.836	0	(<206.8)	ac blower motor
	1235	4.65	0	(<215.1)	dc motor, missile
	-	39.4	0	(<25.4)	dc motor
	-	4.836	0	(<206.8)	dc motor
	-	5.71	0	(<175.1)	dc motor
	-	.3095	0	(<3231.)	dc motor
	-	.3442	0	(<2905.)	dc motor
Missile E-1	874	12.760	0	(<78.4)	dc motor
Missile E-1	874	12.760	0	(<78.4)	antenna spin motor
Missile I	4140	41.18	14	340.	torque motor
TOTALS		190.4772	31	162.7	

6.1.3 Data Evaluation

The non-operating data is recombined in Table 6.1-3 by device type. Failure rates are calculated for the combined data and the one-sided 90% confidence limit is given. The true failure rate should lie below this limit with 90% confidence.

A comparison of the failure rates tends to indicate that the rotating devices with the simpler functions have a better storage reliability. As the complexity of the function increases the failure rate tends to increase. Of course, this is an assumption and other factors may be causing these differences. Due to insufficient data, comparisons cannot be made between environments. The failures attributed to torquer motors may not all be storage related.

A test of significance was performed to determine whether a single failure rate could be applied for all of the devices. This test is described in Appendix A. The test indicated that there was a significant difference in the failure rates and the data could not be pooled for a common failure rate.

A comparison was made between this data and the gyro failure rate in report LC-78-EM1 and the motor driven switch failure rate in report LC-78-EM3. The gyro failure rate of 133 fits and the motor driven switch failure rate of 138 fits falls in the median range of this data. This would indicate that all of these rotating devices are experiencing similar failure mechanisms.

6.1.4 Failure Modes and Mechanisms

Only one source from the non-operating data described above gave a failure mode. Data on Missile I indicated the primary mode of failures for the torque motors was a shorted brake. It is not certain whether this is actually a storage problem or a particular characteristic in the missile design.

One system for which no storage time data was available reported a significant number of motor failures in eight years of storage. The system was stored in a controlled environment and was activated periodically. Investigations showed that the cause of failure was a result of commutator filming. It was attributed to outgassing of either the lubricant or coil impregnant after years of storage.

It is assumed failure mechanisms of these rotating devices would be similar to those reported for other rotating devices in reports LC-78-EM1 (Gyroscopes) and LC-78-EM4 (Switches). The gyro mechanisms were mostly concerned with: spin bearing lubrication (drying and oxidation were chief concerns); low temperature annealing of rotating surfaces; and corrosion of surfaces. The motordriven switch mechanisms includes swelling, cracking and general materiel degradation of O-rings, packing and insulators. Corrosion of bearing, contacts, switch parts, gear assemblies and motor armature were also postulated.

Long life space hardware also experiences some similarities to storage. Some of the applicable failure mechanisms include: inadequate lubrication due to evaporation or migration; oxidation of lubricant; bearing misalignment; improper shaft fit; grinding and housing imperfections; and inadequate lubricant cleanliness.

TABLE 6.1-3. NON-OPERATING DATA BY DEVICE TYPE

TYPE	MILLION NON-OP. PART HOURS	NO. OF FAILURES	FAILURE RATE IN FITS	90% ONE-SIDED CONFIDENCE LIMIT
AC Generator	13.827	11	795.5	1203.
Slip Ring Assy.	8.3257	0	120.1	277.
Torquer Motor	45.338	14	308.8	445.
Resolvers & Synchros	14.196	2	140.9	375.
AC Motor	2.3168	1	431.6	1679.
DC Motor	87.1077	3	34.4	77.
Blowers & Fans	27.682	0	36.1	83.

6.2 Operational Prediction Models

6.2.1 High Speed Motor Operational Prediction Model

The MIL-HDBK-217B failure rate model for hi-speed motors is:

$$\lambda_p = (\lambda_E + \lambda_W)\Pi_E \times 10^{-6}$$

where:

λ_E = electrical failure rate = $\lambda_b \Pi_F$

λ_W = mechanical failure rate = $\dfrac{P_{pop}(10)^4}{t_{op}}$

λ_b = electrical base failure rate

Π_F = motor family & quality factor

t_{op} = motor operating time (hr.) for which λ_p is to be calculated

P_{pop} = percentage of motor mechanical failures during operating period, t_{op}

Π_E = environmental factor

The model, failure rate and adjustment factor values are given in Figures 6.2-1 through 6.2-7.

The base failure rate, λ_b, motor family and quality factor, Π_F and environmental factor, Π_E, values are obtained directly from Figure 6.2-1. To obtain the value for λ_b, the operating hot-spot temperature must be known. If the operating hot-spot temperature is not known or cannot be measured, calculate it approximately: ambient plus 40°C = frame temperature; frame temperature plus 10°C = hot-spot temperature.

The value for t_{op} is the operating time for which λ_p is to be calculated.

The value for P_{pop} is obtained from Figures 6.2-2 through 6.2-7 in two steps:

Step 1 - Enter Figure 6.2-2, -3, or -4 with frame temperature (degrees C) and operating speed (rpm) to obtain lot MTTF. Which figure is used depends upon whether the motor has a commutator or is brushless and (if brushless) whether or not silicone lubricant is used. In Figures 6.2-2 & -3, use linear interpolation between the two frame temperature curves, if necessary.

If frame temperature is unknown, use ambient temperature plus 40 degrees C.

Step 2 - Determine P_{pop}, Figure 6.2-5, 6.2-6 or 6.2-7. The figure to use depends upon whether the motor has Case A, B, or C wearout distribution. Motors in Case A have extremely uniform wearout characteristics whereas those in Case C have little uniformity indicative of poor material and process control. Case B is intermediate and is a common characteristic of many motors. Use Case B (Figure 6.2-6) if details are unknown. Enter the figure with the value, t_{op}/lot MTTF (both in hours) and Operating Load/Rated Load. Read P_{pop} on the abscissa. P_{pop} is the percentage of failures during the operating time, t_{op}.

The value obtained for λ_W is the average mechanical failure rate during the operating time, t_{op}. The motor mechanical failure rate is essentially a wearout type and increases with time, while λ_E has a constant failure rate. If λ_W were calculated for a motor for a given t_{op} (i.e. 4000 hrs.), this λ_W would be valid only up to 4,000 motor operating hours. This value of λ_W should not be considered as constant over the equipment life (e.g. 10 years) unless the motor were replaced at the end of each t_{op} interval, 4000 hrs.

The value for the base failure rate, λ_b, may be calculated from the following equation:

$$\lambda_b = Ae^x$$

where $x = \left(\frac{T + 273}{N_T}\right)^G$

T = operating hot-spot temperature (°C)

e = natural logarithm base, 2.718

A, N_T and G are model constants.

The base failure rate is based on the relationship between the operating hot-spot temperature and the rated insulation hot-spot temperature. Determine the rating of insulation from the specifications or from the supplier's data and the operating hot-spot temperature. The values for the model constants can then be obtained from Table 6.2-1.

TABLE 6.2-1 BASE FAILURE RATE MODEL CONSTANTS

Equation Constants	Rated Insulation Hot-Spot Temperature			
	105°C	130°C	155°C	180°C
A	7.20 $\times 10^{-4}$	6.06 $\times 10^{-4}$	1.83 $\times 10^{-3}$	2.03 $\times 10^{-3}$
N_T	352	364	409	398
G	14.0	8.7	10.0	3.8

FIGURE 6.2-1 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR HI SPEED MOTORS

$$\lambda_p = (\lambda_E + \lambda_W) \Pi_E \times 10^{-6}$$

$$\lambda_E = \lambda_b \Pi_F \qquad \lambda_W = \frac{P_{pop}(10)^4}{t_{op}}$$

λ_b (Base Failure Rate)

T(°C)	Rated Insulation Hot-Spot T.			
	105°C	130°C	155°C	180°C
30	.0008	.0007	.0019	.0029
40	.0009	.0008	.0020	.0030
50	.0010	.0009	.0020	.0032
60	.0011	.0010	.0021	.0034
70	.0014	.0011	.0022	.0036
80	.0020	.0013	.0023	.0038
90	.0033	.0016	.0025	.0041
100	.0068	.0021	.0027	.0044
110	.0188	.0029	.0031	.0048
120		.0043	.0036	.0053
130		.0068	.0043	.0058
140			.0055	.0064
150			.0074	.0072
160			.0107	.0080
170				.0091

P_{pop} (Wear-out percent)

See text and Figures 6.2-2 through 6.2-7.

t_{op} (Operating time)

Motor operating time in hours.

Π_F (Motor Type Factor)

Motor Type		Π_F (Upper Grade)	Π_F (Lower Grade)
Brushless Motors	Polyphase Shaded-pole Synchronous	1	3
	Split-phase Capacitor	1.5	5
Commutator Motors	(rpm) <2,000	2	10
	2,000 to >10,000	6	24
	10,000 to 22,000	20	-

Π_E (Environmental Factor)

Environment	Π_E
Ground, Fixed	1.5
Space Flight	N/A
Airborne, Inhabited	2.5
Naval, Sheltered	4.5
Ground, Mobile	6.0
Naval, Unsheltered	7.7
Airborne, Uninhab.	9.3
Missile, Launch	N/A

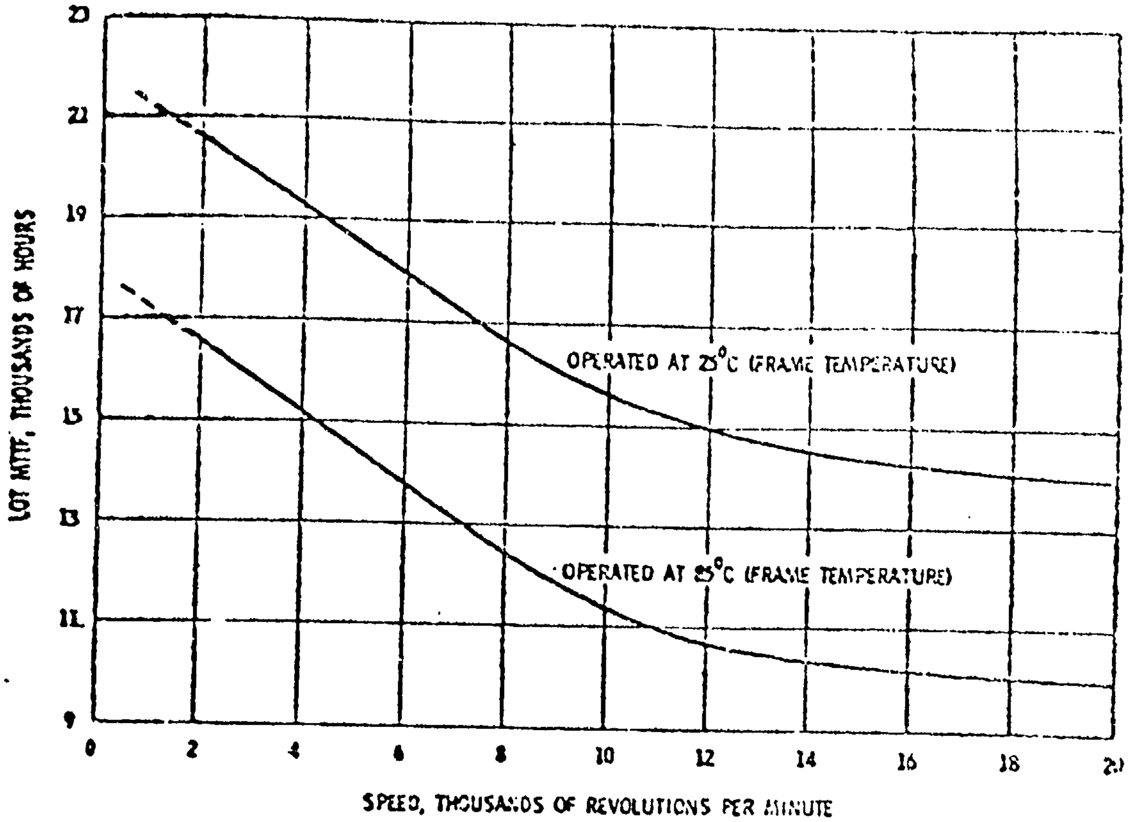

FIGURE 6.2-2. LOT MTTF FOR BRUSHLESS MOTORS (85°C)

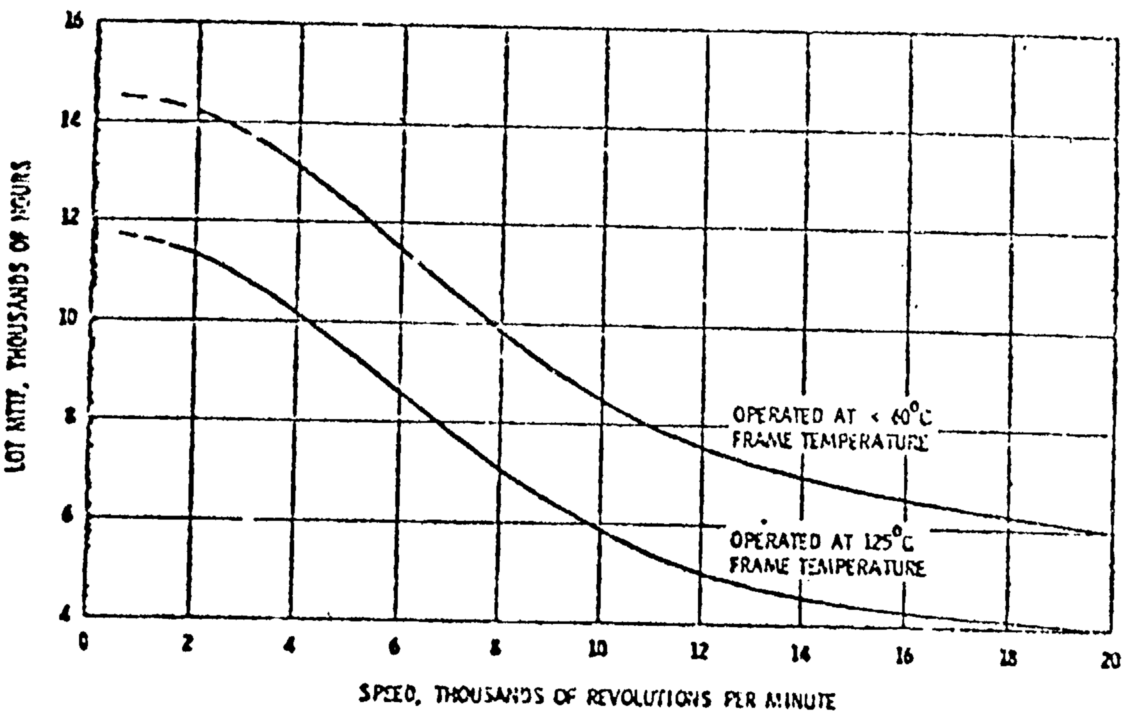

FIGURE 6.2-3. LOT MTTF FOR SILICONE-LUBRICATED BRUSHLESS MOTORS (125°C)

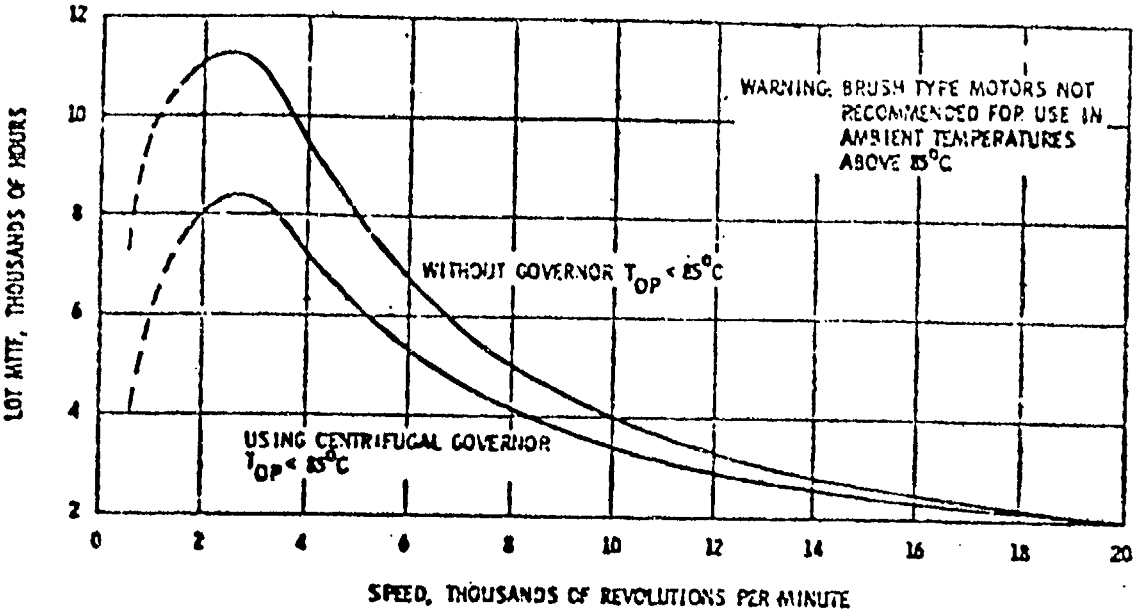

FIGURE 6.2-4. LOT MTTF FOR COMMUTATOR-TYPE MOTORS

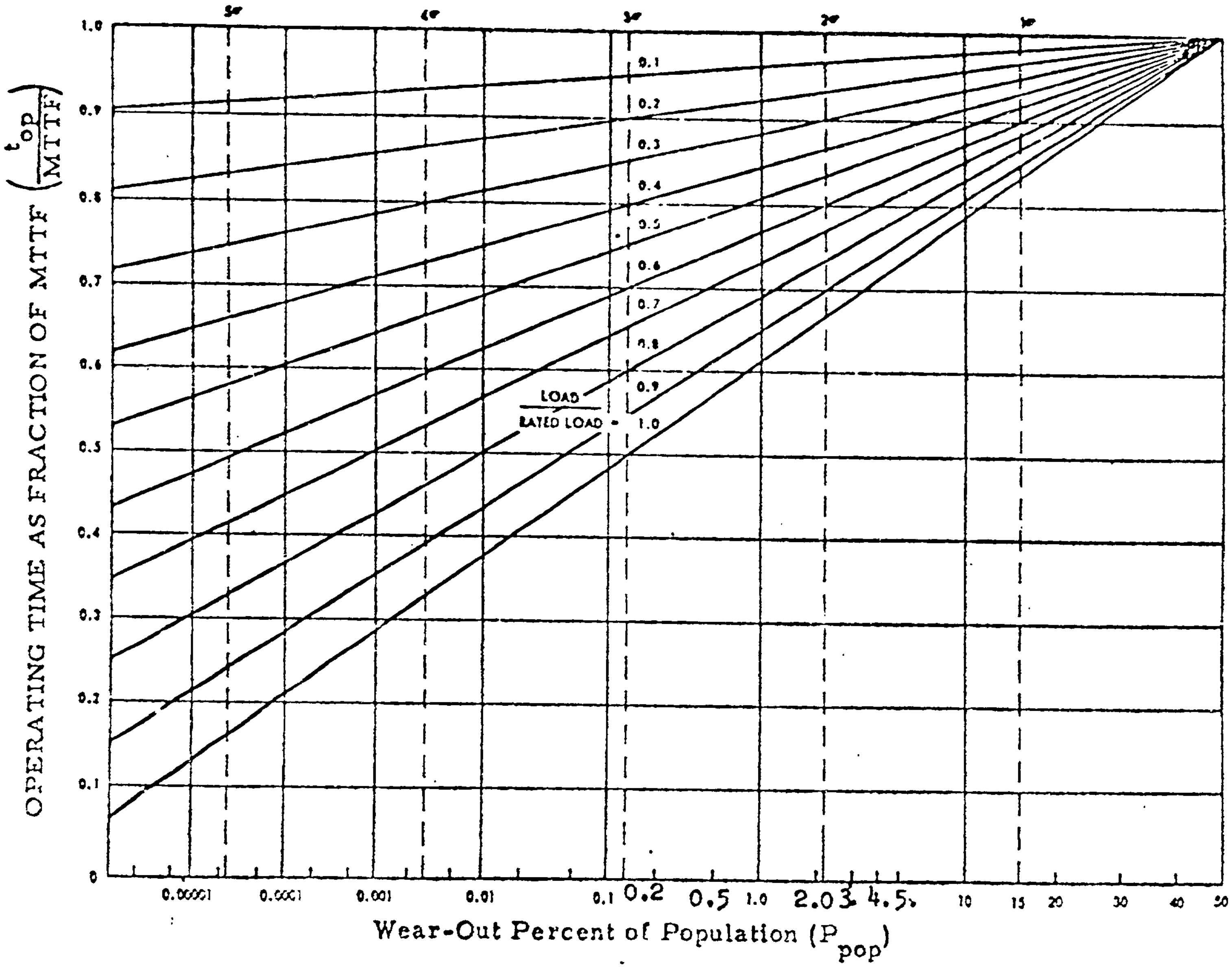

FIGURE 6.2-5. CASE A WEAR-OUT DISTRIBUTION (3σ at 50 Percent MTTF) FOR HIGH SPEED MOTORS

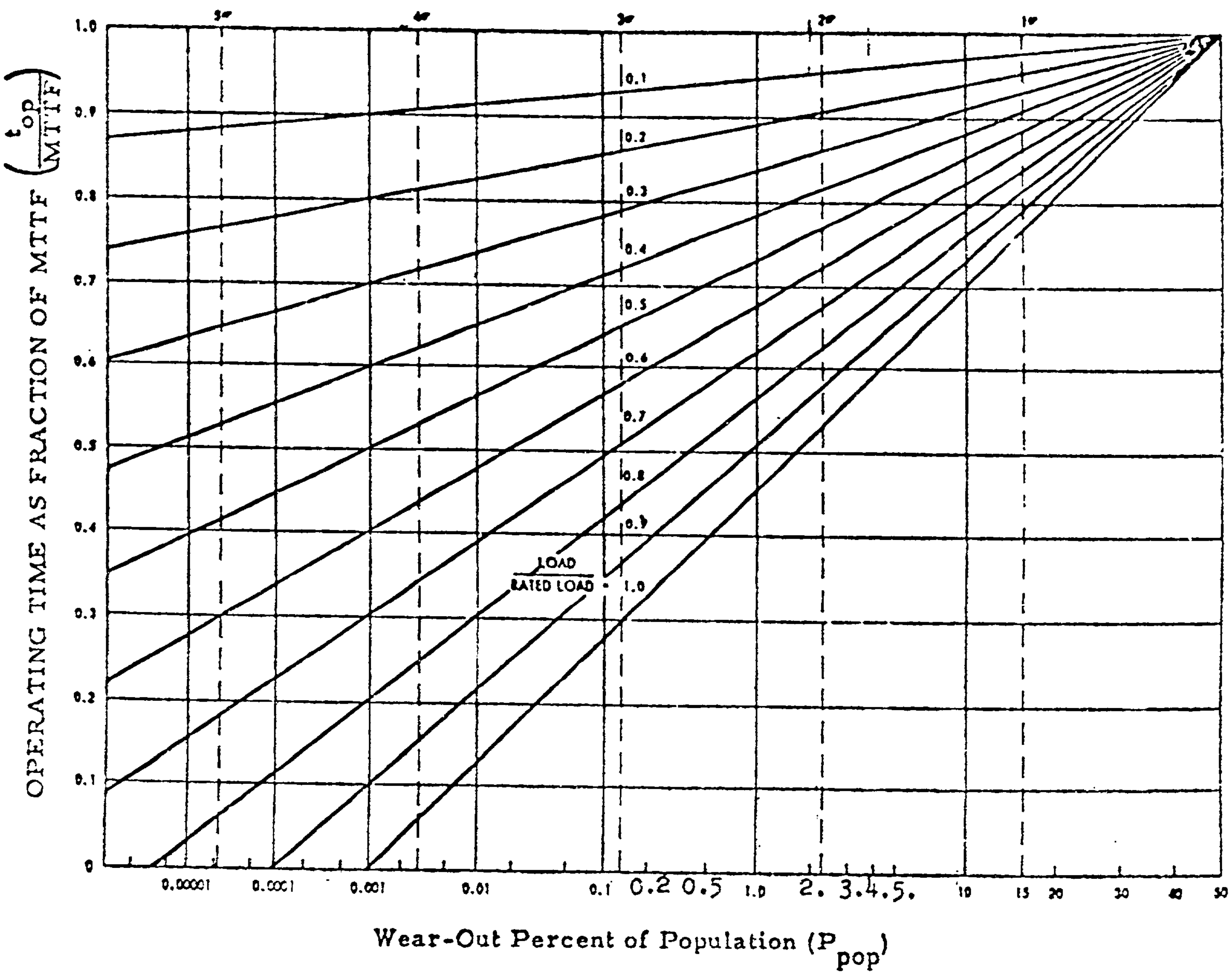

FIGURE 6.2-6. CASE B WEAR-OUT DISTRIBUTION (3σ at 30 Percent MTTF) FOR HIGH SPEED MOTORS

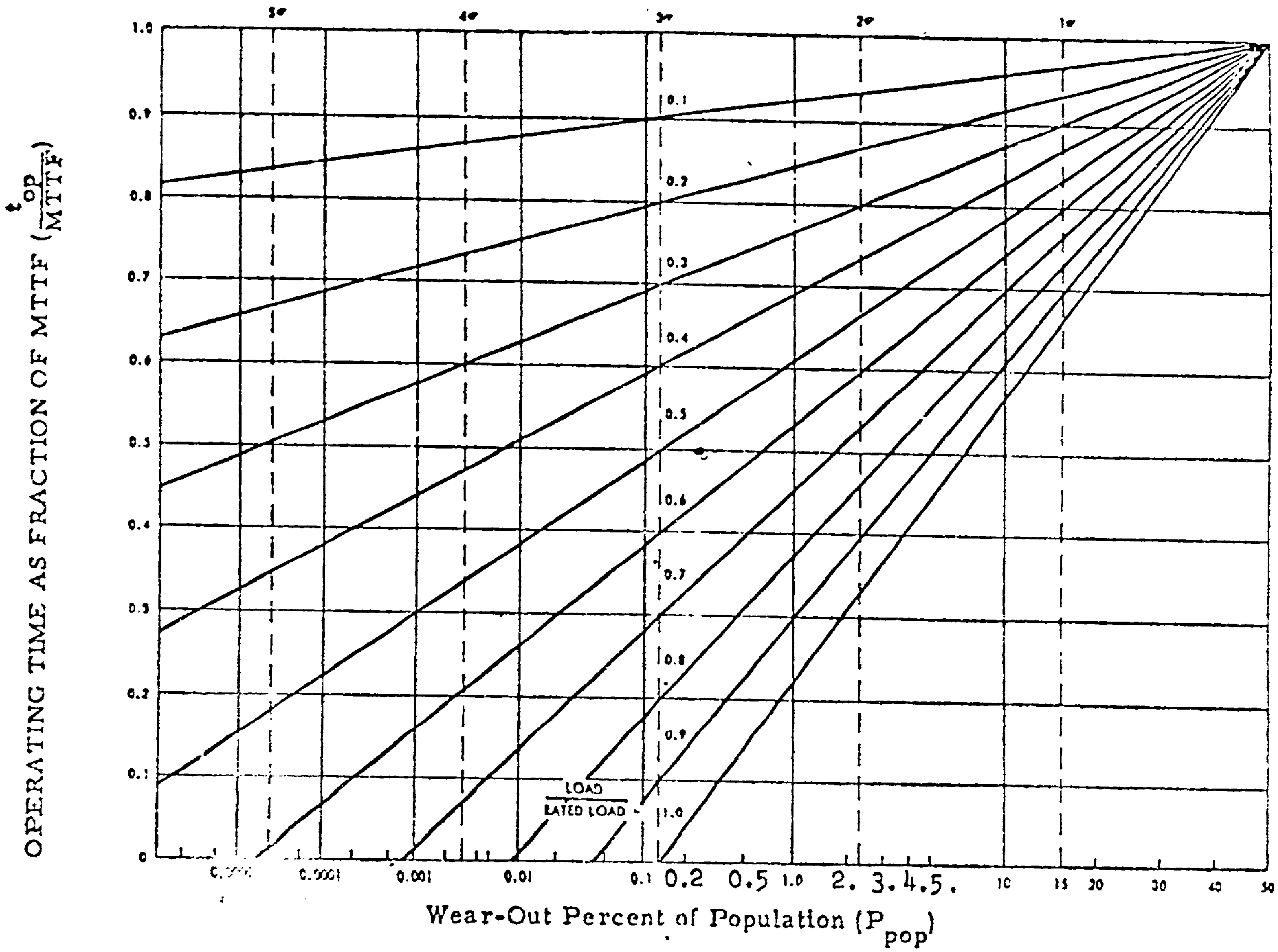

FIGURE 6.2-7. CASE C WEAR-OUT DISTRIBUTION (3σ at 0.0 MTTF) FOR HIGH SPEED MOTORS

6.2.2 Synchros and Resolvers Operational Prediction Model

The MIL-HDBK-217B failure rate model for low-speed, low load synchros and resolvers is:

$$\lambda_p = \lambda_b \, (\Pi_S \times \Pi_N \times \Pi_E) \times 10^{-6}$$

where: λ_p = device failure rate
λ_b = base failure rate
Π_S = Type and Size Adjustment Factor
Π_N = Adjustment Factor for Number of Brushes
Π_E = Environmental Adjustment Factor

The model, base failure rate and adjustment factor values are given in Figure 6.2-8.

Synchros and resolvers are predominantly used in service requiring only slow and infrequent motion. Mechanical wear-out problems are not serious so that the electrical failure mode can predominate, and no mechanical mode failure rate is required in the model above.

The values for the base failure rate may be calculated from the following equation:

$$\lambda_b = Ae^{\left(\frac{T + 273}{N_T}\right)^G}$$

where T is the frame temperature in °C.
and e is natural logarithm base, 2.718
A, N_T and G are model constants.

The base failure rate is based on the frame temperature of the synchro or resolver. When the actual frame temperature is not known, assume ambient plus 40°C.

The values for the model constants can be obtained from Table 6.2-2.

TABLE 6.2-2. BASE FAILURE RATE MODEL CONSTANTS

Equation Constants	Value
A	0.535×10^{-2}
N_T	334
G	8.5

FIGURE 6.2-8. MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR LOW SPEED, LOW LOAD SYNCHROS AND RESOLVERS

$$\lambda_P = \lambda_b (\pi_S \times \pi_N \times \pi_E) \times 10^{-6}$$

λ_b (Base Failure Rate)

T(°C)	λ_b	T(°C)	λ_b
30	.0083	85	.0325
35	.0088	90	.0407
40	.0095	95	.0523
45	.0103	100	.0690
50	.0114	105	.0937
55	.0126	110	.131
60	.0142	115	.191
65	.0162	120	.288
70	.0187	125	.453
75	.0221	130	.744
80	.0265	135	1.28

π_S (Type and Size Factor)

Device Type	Size 8 or Smaller	Size 10-16	Size 18 or Larger
Synchro	2	1.5	1
Resolver	3	2.25	1.5

π_N (Factor for Number of Brushes)

Number of Brushes	Upper Quality Grade	Lower Quality Grade
2	1	2
3	1.5	4
4	2	5

π_E (Environmental Factor)

Environment	Upper Quality Grade	Lower Quality Grade
Ground, Benign	1.0	2.0
Space Flight	N/A	N/A
Ground, Fixed	1.3	2.5
Airborne, Inhabited	3.0	6.0
Naval, Sheltered	6.0	13.0
Ground, Mobile	8.0	18.0
Naval, Unsheltered	10.0	22.0
Airborne, Uninhab.	12.0	26.0
Missile, Launch	N/A	N/A

6.2.3 MIL-HDBK-217B Blowers and Fans Prediction Model

This section describes the method for calculating the failure rates of blowers and fans meeting the requirements of MIL-B-23071B which are designated UQG (Upper Quality Grade) and blowers and fans constructed to commercial standards which are designated LQG (Lower Quality Grade). Failure rates of blowers and fans are not constant but are found to be increasing with time. The failure rates derived by the methods presented in this section are average rates resulting from the averaging of the cumulative hazard rate over the period of time, t, as defined in equations (1) and (2). The failure rates are strongly influenced by the thermal conditions of the application and particularly by the presence of thermal cycling. It is important, for this reason, that the thermal environment be accurately determined and the proper models of this section employed in developing the failure rate. Other environmental stresses do not have a significant effect on the failure rate. Therefore, no additional environmental or application modifying factors are required.

The failure rate models are presented in Figures 6.2-9 thru 6.1-12.

FIGURE 6.2-9 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR BLOWERS AND FANS

MODEL FOR FIXED SERVICE LIFE

$$\lambda_{t_1} = \left[\frac{t_1^2}{\alpha_B^3} + \frac{t_1^{.76}}{\alpha_W^{1.76}}\right] \text{ X } 10^6 \text{ (failures/} 10^6 \text{ hours)}$$

t_1 - SERVICE LIFE

t_1 = End of Service Life in hours.

α_B - BEARING WIEBULL CHARACTERISTIC LIFE

See Figure 6.2-11

α_W - WINDING WIEBULL CHARACTERISTIC LIFE

See Figure 6.2-12

MODEL FOR UNLIMITED SERVICE LIFE

$$\lambda_{t_2} = \left[\frac{t_2^2}{\alpha_B^3} + \frac{t_2^{.76}}{\alpha_W^{1.76}}\right] \text{ X } 10^6 \text{ (failures/} 10^6 \text{ hours)}$$

t_2 - ESTIMATED MTBF

Graphic Solution of MTBF (t_2)
$t_2 = S \text{ X } \alpha_B$ S is obtained from Figure 6.2-10 as a function of α_B/α_W. when $\frac{t_2}{\alpha_W} = 0$, $t_2 = .885\ \alpha_B$

Model Solution of MTBF (t_2)
$0.5 = 1 - e^{-\left[\left(\frac{t_2}{\alpha_B}\right)^3 + \left(\frac{t_2}{\alpha_W}\right)^{1.76}\right]}$

FIGURE 6.2-10 S VALUE FOR ESTIMATE OF MTBF(t_2)

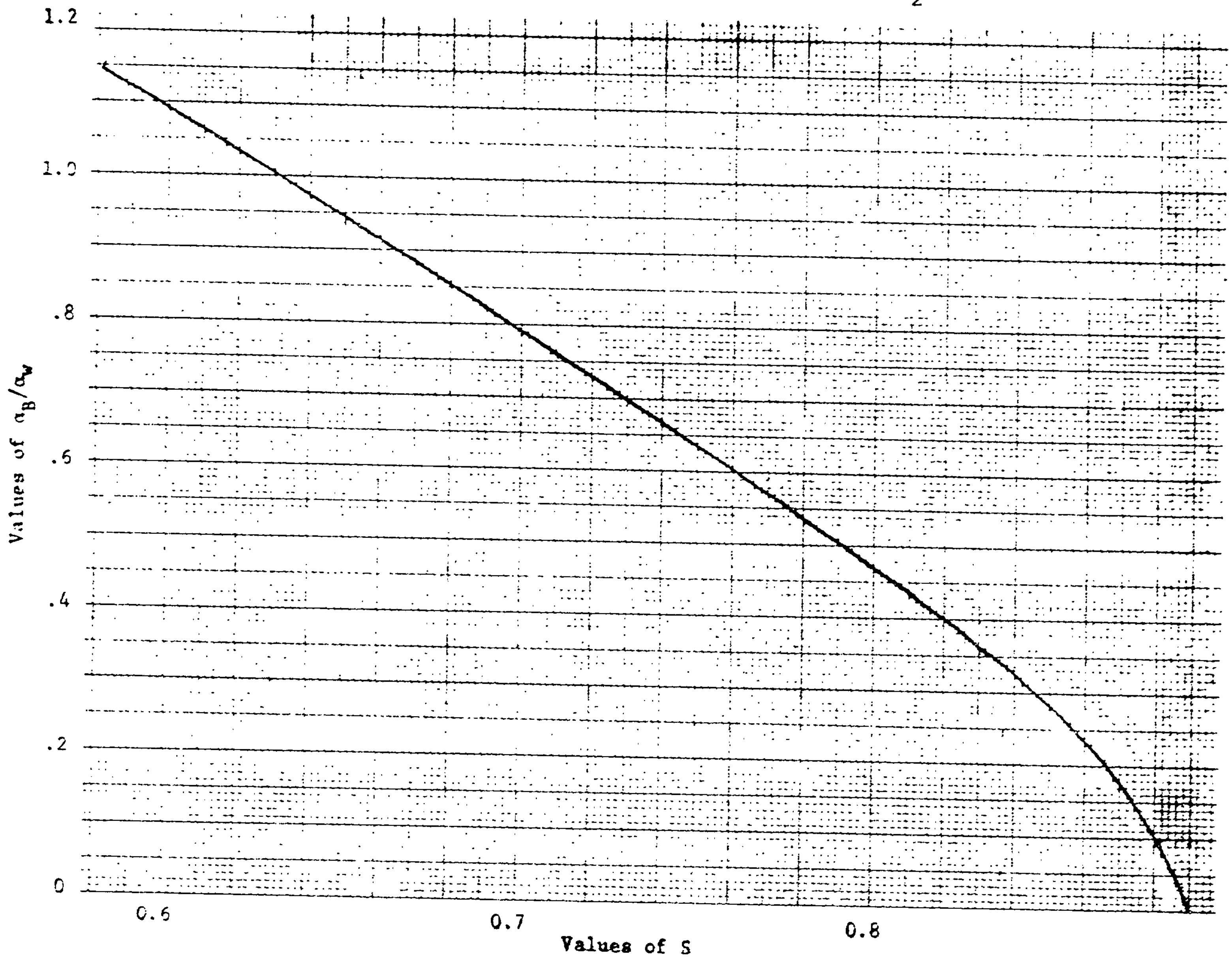

FIGURE 6.2-11 α_B* - BEARING WEIBULL CHARACTERISTIC LIFE FOR BLOWERS AND FANS

α_B - BEARING WIEBULL CHARACTERISTIC LIFE

Bearing Temperature	Model
$349^\circ K$ or lower	$\text{Log } \alpha_B = - \frac{2450}{T_B} + B$
$350^\circ K$ or higher	$\text{Log } \alpha_B = \frac{2450}{T_B} - K_g - q \frac{DN}{DN_L}$

T_B - BEARING TEMPERATURE

$$T_B = ({}^\circ C_{ambient} + \Delta {}^\circ C_{winding\ rise} - 10^\circ C + 273^\circ)\ {}^\circ K$$

$\Delta {}^\circ C = 50^\circ C$ if unknown

DN - DIAMETER/SPEED FACTOR

DN = Bearing Bore Diameter (mm) X Speed (rpm)

DN_L, q, B, K_g

See Next Page

α_B - BEARING WEIBULL CHARACTERISTIC LIFE FROM THERMAL CYCLING

$$\alpha_B = 0.5 \frac{\left(h_1 + h_2 + h_3 + \cdots + h_m\right)}{\left(\frac{h_1}{\alpha_{B_1}} + \frac{h_2}{\alpha_{B_2}} + \frac{h_3}{\alpha_{B_3}} + \cdots + \frac{h_m}{\alpha_{B_m}}\right)}$$

α_{B_i} - BEARING CHARACTERISTIC LIFE AT TEMPERATURE T_i

α_{B_1} = Bearing characteristic life at T_1

α_{B_2} = Bearing characteristic life at T_2

α_{B_m} = Bearing characteristic life at T_m

$$T_2 = \frac{T_1 + T_3}{2} \; ; \quad T_m = \frac{T_{m-1} + T_1}{2}$$

h_i - TIME AT TEMPERATURE OR TIME TO CYCLE TEMPERATURE

h_1 = time at temperature T_1

h_2 = time to cycle from temperature T_1 to T_3

h_3 = time at temperature T_3

h_m = time to cycle from temperature T_{m-1} to T_1

* For UQG units use α_B = 120,000 hours if computed α_B exceeds 120,000 hours.
For LQG units use α_B = 80,000 hours if computed α_B exceeds 80,000 hours.

FIGURE 6.2-11 α_B - BEARING WEIBULL CHARACTERISTIC LIFE FOR BLOWERS AND FANS (CONTINUED)

K_g - Grease Factor

Grease	Fluid	Soap	Mil. Spec.	Conservative Upper Temp. Limit °C	K_g Value
A	Diester	Sodium & Solid		177	1.73
B*	Silicon	Lithium		150	2.16
C	Diester	Lithium	MIL-G-23827	100	1.95
D	Syn. Hydro Carbon	Non-Soap	MIL-G-81322	177	1.92
E	Mineral	Sodium	MIL-G-18709	100	1.88
F	Unknown Grease				2.00

*Limiting DN for Grease B is 200,000. This value should be used if lower than limiting DN value for Bearing.

DN_L - LIMITING FACTOR

Bearing Bore (in)	Bearing Bore (mm)	LQG ABEC*-1&3	UQG ABEC-5&7
.125	3.175	190,000	285,000
.1875	4.76	210,000	315,000
.250	6.35	230,000	340,000
other	other	200,000	300,000
unknown	unknown	200,000	-

*ABEC-Annular Bearing Engineering Committee

q & B - QUALITY FACTORS

Quality	q	B
UQG - Mil Spec Quality	.26	12.3
LQG - Commercial Quality	.95	12.0
Unknown	.95	12.0

FIGURE 6.2-12 α_W - WINDING WEIBULL CHARACTERISTIC LIFE FOR BLOWERS AND FANS

α_W - WINDING CHARACTERISTIC LIFE

$$\text{Log } \alpha_W = \frac{4170}{T_W} - A$$

A - INSULATION QUALITY FACTOR

Insulation Class	A	
	UQC	LQG
H	5.259	5.593
F	5.797	6.131
B	6.391	6.735
A	7.085	7.419
unknown	-	7.0

T_W - WINDING TEMPERATURE

T_W = ($^\circ C_{ambient}$ + $\Delta^\circ C$ + $10^\circ C$ + $273^\circ C$) $^\circ K$

$\Delta^\circ C$ = $50^\circ C$ if unknown

α_W* - WINDING CHARACTERISTIC LIFE RESULTING FROM THERMAL CYCLING

$$\alpha_W = 0.5 \frac{\left(h_1 + h_2 + h_3 + \cdots + h_m\right)}{\left(\frac{h_1}{\alpha_{W_1}} + \frac{h_2}{\alpha_{W_2}} + \frac{h_3}{\alpha_{W_3}} + \cdots + \frac{h_m}{\alpha_{W_m}}\right)}$$

α_{W_i} - WINDING CHARACTERISTIC LIFE AT TEMPERATURE T_i

α_{W_1} = Winding Characteristic Life at T_1

α_{W_2} = Winding Characteristic Life at T_2

α_{W_m} = Winding Characteristic Life at T_m

$$T_2 = \frac{T_1 + T_3}{2} \; ; \quad T_m = \frac{T_{m-1} + T_1}{2}$$

h_i - TIME AT TEMPERATURE OF TIME TO CYCLE TEMPERATURE

h_1 = time at temperature T_1

h_2 = time to cycle from temperature T_1 to T_3

h_m = time to cycle from temperature T_{m-1} to T_1 (usually the time to return to T_1)

* Do not compute α_W in a thermal cycling environment if the winding diameter exceeds .995 inches. The fraction t_2/α_W is assumed = 0 and t_2 = .885α_B .

6.3 Operational/Non-Operational Reliability Comparison

Operational failure rate data for rotating devices were extracted from report RADC-TR-64-268, Revision of RADC Non-electronic Reliability Notebook, D. F. Cottrell, et al, Martin Marietta Aerospace, dated October 1974. This data is shown in Tables 6.3-1 through 6.3-5 and compared with the non-operating failure rate prediction. Comparing the common environment (ground), the non-operating to operating ratio ranges from 1:2 for ac motors to 1:658 for ac generators.

TABLE 6.3-1. OPERATIONAL/NON-OPERATIONAL RELIABILITY COMPARISON - BLOWERS AND FANS

ENVIRONMENTS	PART HRS. (10^6)	NO. OF FAILURES	FAILURE RATE IN FITS	$\lambda_{op}/\lambda_{no}$
Non-Operating				
Ground, Fixed	27.682	0	36.1	-
Operating				
Ground	32.306	46	1424.	39.
Ground, Mobile	19.139	108	5643.	156.
Airborne	48.620	2132	44123.	1222.
Helicopter	2.027	173	85348.	2364.
Submarine	10.953	5	456.	13.
Shipboard	6.072	112	18445.	511.

TABLE 6.3-2. OPERATIONAL/NON-OPERATIONAL RELIABILITY COMPARISON - ELECTRIC MOTORS

ENVIRONMENT	PART HRS. (10^6)	NO. OF FAILURES	FAIL. RATE IN FITS	$\lambda_{op}/\lambda_{no}$ dc	$\lambda_{op}/\lambda_{no}$ ac	$\lambda_{op}/\lambda_{no}$ torquer
Non-Operating						
Ground, Fixed						
dc	87.1077	3	34.4	-	-	-
ac	2.3168	1	431.6	-	-	-
Torquer	45.338	14	308.8	-	-	-
Operating						
Satellite	2.295	2	871.	25.	2.	3.
Ground	6.509	9	1383.	40.	3.	4.
Ground, Mobile	1.095	10	9132.	265.	21.	30.
Airborne	5.085	785	154376.	4488.	358.	500.
Helicopter	.110	21	190909.	5550.	442.	618.
Submarine	.234	11	47009.	1367.	109.	152.
Shipboard	.014	0	(<71429.)	2076.	165.	231.

TABLE 6.3-3. OPERATIONAL/NON-OPERATIONAL RELIABILITY COMPARISON - SYNCHROS AND RESOLVERS

ENVIRONMENT	PART HRS. (10^6)	NO. OF FAILURES	FAIL. RATE IN FITS	$\lambda_{op}/\lambda_{no}$
Non-Operating				
Ground, Fixed	14.196	2	140.9	-
Operating				
Ground, Mobile	6.908	29	4198.	30.
Airborne	.625	18	28800.	204.
Helicopter	.100	15	150000.	1065.
Submarine	8.506	3	353.	3.

TABLE 6.3-4 OPERATIONAL/NON-OPERATIONAL RELIABILITY COMPARISONS - AC Generators

ENVIRONMENT	PART HRS. (10^6)	NO. OF FAILURES	FAILURE RATE IN FITS	$\lambda_{op}/\lambda_{no}$
Non-Operating				
Ground, Fixed	13.827	11	795.5	-
Operating				
Ground, Mobile	.086	45	523256.	658.
Airborne	5.444	6017	1105253.	1389.
Helicopter	.015	7	466667.	587.
Shipboard	.341	8	23460.	29.

TABLE 6.3-5. OPERATIONAL/NON-OPERATIONAL RELIABILITY COMPARISONS - Slip Ring Assemblies

ENVIRONMENT	PART HRS. (10^6)	NO. OF FAILURES	FAILURE RATE IN FITS	$\lambda_{op}/\lambda_{no}$
Non-Operating				
Ground, Fixed	8.3257	0	(<120.1)	-
Operating				
Satellite	.408	0	(<2451.)	20.
Ground	.437	0	(<2288.)	19.
Ground, Mobile	2.065	103	49879.	415.
Helicopter	.014	3	214286.	1784.
Submarine	.977	39	39918.	332.

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7.0 Miscellaneous Electromechanical Devices

Table 7-1 summarizes the non-operating data for a variety of miscellaneous electromechanical devices.

TABLE 7-1. MISCELLANEOUS ELECTROMECHANICAL DEVICE NON-OPERATING DATA

SOURCE	DEVICE	NO. OF DEVICES	MILLION NON-OP HRS	NO. OF FAILURES	FAILURE RATE IN FITS
A	Transducers, Pressure	-	2.002	4	1998.
B	Transducer	42	.0882	0	(< 11338.)
TOTALS (Transducers)			2.0902	4	1914.
Missile H	Antenna Assy. Hydr. Actuated	4284	68.1	1	15.
Missile E-1	Antenna Assy. Elec. Actuated	874	12.76	0	(<78.)
C	Antenna Assy.	-	.9286 2.2299	0 0	(<1076.) (<448.)
B	Antenna Assy.	8	.0456	0	(<21930.)
R	Antenna Assy.	38	1.640	0	(<610.)
A	Antenna Assy.	-	.610	0	(<1639.)
TOTALS (Antenna Assys.)			85.704	1	11.7
C	Rotary Inverter	-	21.6	0	(<46.3)
B	Timer & Clocks	7	.0178	0	(<56180.)
B	Indicators	58	.0046	0	(<217391.)
A	Flight Inst., Missile	-	264.00	25	94.7

APPENDIX A

TEST OF SIGNIFICANCE OF DIFFERENCES IN FAILURE RATES (MORE THAN TWO POPULATIONS)

The storage reliability data is obtained from numerous sources. A detailed qualitative analysis is performed on the data to classify devices, environments, uses, quality levels, failures modes & mechanisms, and so on. Once the data sets are grouped according to these analyses, it is still not certain whether grouped sets of failure data are in truth from the same statistical population. It is possible that the failure rate characteristics of identical devices from the same manufacturers, with the same application, use environment, and so on, are not from the same population in terms of reliability -- possibly due to some problem on a production line for a certain lot or other factor.

Therefore a statistical test is performed to determine if the different data sets could be from the same statistical population.

The technique used is for more than two data sets and is taken from "Statistical Methods for Research Workers," R. A. Fisher, 13th edition, Hufner, 1963, pages 99-101.

The techniques assumes that the underlying failure distributions each have the same constant failure rate (λ). Therefore, the probability of a number of failures for each population can be represented by the Poisson distribution.

A single failure rate is calculated based on the pooled data sets being tested.

$$\lambda = \frac{\sum_{i=1}^{N} f_i}{\sum_{i=1}^{N} T_i}$$

where λ = Mean failure rate for all data sets

f_i = the number of failures in data set i

T_i = the total storage hours in data set i

n = the number of data sets being tested

The expected number of failures and the difference between the expected number of failures and actual failures is calculated for each data set based on the pooled data:

$$M_i = \lambda T_i$$

$$d_i = |f_i - m_i|$$

where

M_i = expected number of failures for data set: (based on the pooled data sets)

d_i = absolute value of the differences between the expected number of failures and the actual failures for data set i.

Next, lower and upper limits are calculated for the Poisson distribution:

$$U_i = [M_i + d_i] \text{ (if } U_i = f_i\text{, set } U_i = f_i - 1)$$

$$L_i = \langle M_i - d_i \rangle \text{ (if } L_i = f_i\text{, set } L_i = f_i + 1)$$

$$\text{(if } L_i < 0\text{, set } L_i = 0)$$

U_i = upper limit for data set i

L_i = lower limit for data set i

[ ] = rounded down to integer value

< > = rounded up to integer value

The probability that f_i failures would occur in data set i given the population failure rate is λ, is expressed by the Poisson distribution:

$$P_i = 1 - \sum_{j=L_i}^{U_i} P_{ij}$$

$$= 1 - \sum_{j=L_i}^{U_i} e^{-M_i} \frac{M_i^{\,j}}{j!}$$

The individual probabilities, P_i, are the significance probabilities for the individual distributions. It is required to test whether the ensemble of P_i taken together represents an improbable configuration under the null hypothesis which is that the underlying distributions have the same constant failure rate (λ).

The test is done as follows:

$$C_i = -2 \ln P_i$$

$$C = \sum_{i=1}^{n} C_i$$

Find Cr for $\alpha = .05$ (5% level of significance) and 2n degrees of freedom from the tables of chi square.

If C>Cr reject the null hypothesis (that all of the populations have the same failure rate.)

If the null hypothesis is not rejected, the data sets can be pooled and the common failure rate λ used.

If the null hypothesis is rejected, engineering and statistical analysis is required to remove data sets from the pooled data until the null hypothesis is not rejected.

EXAMPLE 1:

DATA SET	T_i	F_i	M_i	d_i	U_i	L_i	P_i	C_i
1	587.4	19	12.9	6.1	18	7	.0936	4.74
2	144.1	0	3.2	3.2	3	1	.0849	4.93
3	65.6	1	1.4	.4	2	2	1.000	0
4	95.8	1	2.1	1.1	3	2	.5406	1.23
5	128.	3	2.8	.2	3	3	1.000	0
6	281.	15	6.2	8.8	14	0	.0018	12.60
7	78.6	2	1.7	.3	1	1	1.000	0
8	484.8	0	10.7	10.7	21	1	.0016	12.93
	1865.6	41					ΣC_i	= 36.43

pooled - λ = 21.98 fits

C = 36.43

2n degrees of freedom = 16

(from chi-square dist. at $\alpha = .05$) Cr = 26.30

Since C>Cr ---- the null hypothesis, that all of the populations have the same failure rate, is rejected.

EXAMPLE 2:

DATA SET	T_i	f_i	M_i	d_i	U_i	)	P_i	C_i
1	587.4	19	19.5	.5	20	20	1.0	0
2	65.6	1	2.2	1.2	3	2	.536	1.2
3	95.8	1	3.2	2.2	5	2	.277	2.57
4	128.	3	4.2	1.2	5	4	.641	.89
5	281.	15	9.3	5.7	14	4	.070	5.33
6	78.6	2	2.6	.6	3	3	1.02	.0
	1236.4	41						9.99

Pooled λ = 33.16 fits

C = 9.99

2n degrees of freedom = 12

Cr = 21.03

C<Cr - accept null hypothesis --

All data sets have the same failure rate (λ = 33.16 fits).

APPENDIX B

ENVIRONMENTAL DESCRIPTION

Environment	Nominal Environmental Conditions
Ground, Benign	Nearly zero environmental stress with optimum engineering operation and maintenance.
Space, Flight	Earth orbital. Approaches Ground, Benign conditions without access for maintenance. Vehicle neither under powered flight nor in atmospheric re-entry.
Ground, Fixed	Conditions less than ideal to include installation in permanent racks with adequate cooling air, maintenance by military personnel and possible installation in unheated buildings.
Ground, Mobile (and Portable)	Conditions more severe than those for Ground, Fixed, mostly for vibration and shock. Cooling air supply may also be more limited, and maintenance less uniform.
Naval, Sheltered	Surface ship conditions similar to Ground, Fixed, subject to occasional high shock and vibration.
Naval, Unsheltered	Nominal surface shipborne conditions but with repetitive high levels of shock and vibration.
Airborne, Inhabited	Typical cockpit conditions without environmental extremes of pressure, temperature, shock and vibration.
Airborne, Uninhabited	Bomb-bay, tail, or wing installations where extreme pressure, temperature, and vibration cycling may be aggravated by contamination from oil, hydraulic fluid, and engine exhaust. Classes I and Ia equipment of MIL-E-5400 should not be used in this environment.
Missile, Launch	Severe conditions of noise, vibration, and other environments related to missile launch, and space vehicle boost into orbit, vehicle re-entry and landing by parachute. Conditions may also apply to installation near main rocket engines during launch operations.